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*Contract Summary Report
Contract DAAA21-93-D-0001
Task Order No. 001*

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Introduction

*Contract Summary Report
Contract DAAA21-93-D-0001
Task Order No. 0001*

Development of Alternate 7.62mm Tracer Formulations

Task Order No. 0001, Development of Alternate 7.62mm Tracer Formulations, addresses several shortcomings of the currently fielded red-orange bullet tracers, including performance in adverse weather conditions and performance with night vision equipment. The effort that was required consisted of: the design and development of one tracer formulation, suitable for the 7.62mm NATO tracer round, for each of four specified spectral frequencies.

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Section 1

Summary

The synthesis of each of the specified tracer colors, was performed using an understanding of the chemistry of pyrotechnics as well as military operational requirements. As various combinations of chemicals combine in an exothermic reaction, different colors are emitted in a predictable way and it is possible to predict, with a reasonable level of certainty, the relative intensity and color purity associated with each of the formulations. The results of this task were very positive, in that all of the objectives were met. In order to develop the required formulations, and to validate the chemistry of the chemical constituents, each of the colors was realized by at least four different formulations. Each of these formulations has certain advantages and disadvantages that are discussed in this report. In order to satisfy the requirements of the Statement of Work, one formulation for each of the four colors was selected as the recommended output of this task. However, the other formulations may have certain advantages, and their characteristics and performance are reported.

The tracer color requirements were specified in two ways. First the color to be observed was specified, relating to visual perception by a human observer; and then a wavelength region was specified. This implied two related constraints on the tracer output - a quantitative and a qualitative requirement. In the case of the one infrared tracer, the spectral region was the only stated requirement.

In order to quantify the characteristics of the tracer formulations, several dedicated tracer spectrometers were designed and constructed, and used to record the characteristics of the tracer outputs with a digital oscilloscope that recorded the in-band intensity and burn time to a DOS compatible format that was then used to generate graphs. At the same time, visual observations were noted.

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Section 2 of this report discusses the relevant chemistry of pyrotechnic phenomena that yields the desired colors. This discussion considers the balance between the electron transitions that produce specific colors, and the black body radiation which produces various intensities, depending on the burn temperature and emissivity of the mixture. This section discusses how the mixtures for the specified colors were derived, and what the tradeoffs were. This discussion of tracer chemistry is related to the discussion in Section 3, which addresses several issues related to color perception and the human visual system. It is important to understand the differences between color perception in full daylight and at night, and how the sensitivity to the human eye is related to the color. One important fact that is pointed out in this section is that the eye is considerably more sensitive to yellow and green than to red, although the chemical phenomenology emits more energy in the red portion of the visible spectrum.

The procedures that was used to fabricate the actual tracers that were tested are described in Section 4. This includes a discussion of the tooling that was constructed to fabricate pellets and to then insert the pellets into the tracer cavity. The procedures that were followed were designed to simulate actual firing conditions as closely as possible. The simulated bullet had a cavity the same size as the 7.62mm tracer round, and was designed to be spun in a fixture at approximately 21,000 rpm, with air blowing by in order to reasonably simulate atmospheric boundary conditions for actual projectile flight.

The most important issues are those that relate to the quantitative evaluations of tracer performance and how they relate to visual perception. Section 5 addresses how the human eye perceives colors from the point of view of the radiometry of tracers. This section also describes the instrumentation we used to measure the absolute in-band radiation in the specified spectral regions, how this equipment was calibrated, how we made the measurements (both statically and spinning) and the results we obtained for each formulation that was tested. It is important to note that there are several discrepancies between visual perception and the spectral regions that were specified, and we feel this is an area that warrants further investigation.

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The observations and results for each of the four colors are summarized and discussed in Section 6, where the best mixture is selected. When we analyze the burn times and intensities, it is not always clear which is the one best mixture, and the reasoning that has led to our choice is discussed.

Section 7 then looks at the work that was accomplished and where additional investigation is advisable before a product decision is made. Several specific recommendations are made.

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Section 2

Issues Relating to the Synthesis of Distinct Colors

1. Theory of the Production of a Colored Flame

Making colored light from the combustion of a pyrotechnic mixture involves providing for a material which when present in the combustion products of the flame will be thermally excited to emit photons in the desired electromagnetic spectrum. From a practical applications point of view, this can be a somewhat complicated process, since many of the materials identified to be suitable colored light emitters exist briefly only as byproducts of combustion. In addition, too cool a flame temperature may not provide enough thermal energy to cause the material to emit light; too hot a temperature may cause the material to decompose in the flame resulting in reduced colored light output; and the reaction of other materials in the flame may result in blackbody radiation and the subsequent emission of white or other undesirable spectral bands which may overpower and obscure the desired flame color. Pyrotechnicians have identified many molecules and atoms which, when present in a flame of appropriate temperature, will emit light of a particular frequency. Figure 1 shows a chromaticity diagram¹ with flame spectra of fireworks compositions. The molecules along the perimeter of the diagram are those which must be present in the flame to give the color within the identified bandwidths.

Practical colored light emitting pyrotechnic mixtures typically contain a mixture of an oxidizer, metallic fuel, and a small amount of organic fuel. The oxidizer is a salt molecule which contains oxygen to sustain combustion and the metallic atom responsible for the characteristic color output. An example is Strontium Nitrate -- $\text{Sr}(\text{NO}_3)_2$. Its active ingredients are oxygen and strontium. Referring to figure 1, strontium, when combined with chlorine in the combustion flame forms SrCl , which emits red light in the spectral band between approximately 6150Å to 6400Å. To

¹Shimizu, Dr. Takeo Fireworks From a Physical Standpoint, Part II, Pyrotechnica Publications, 1983.

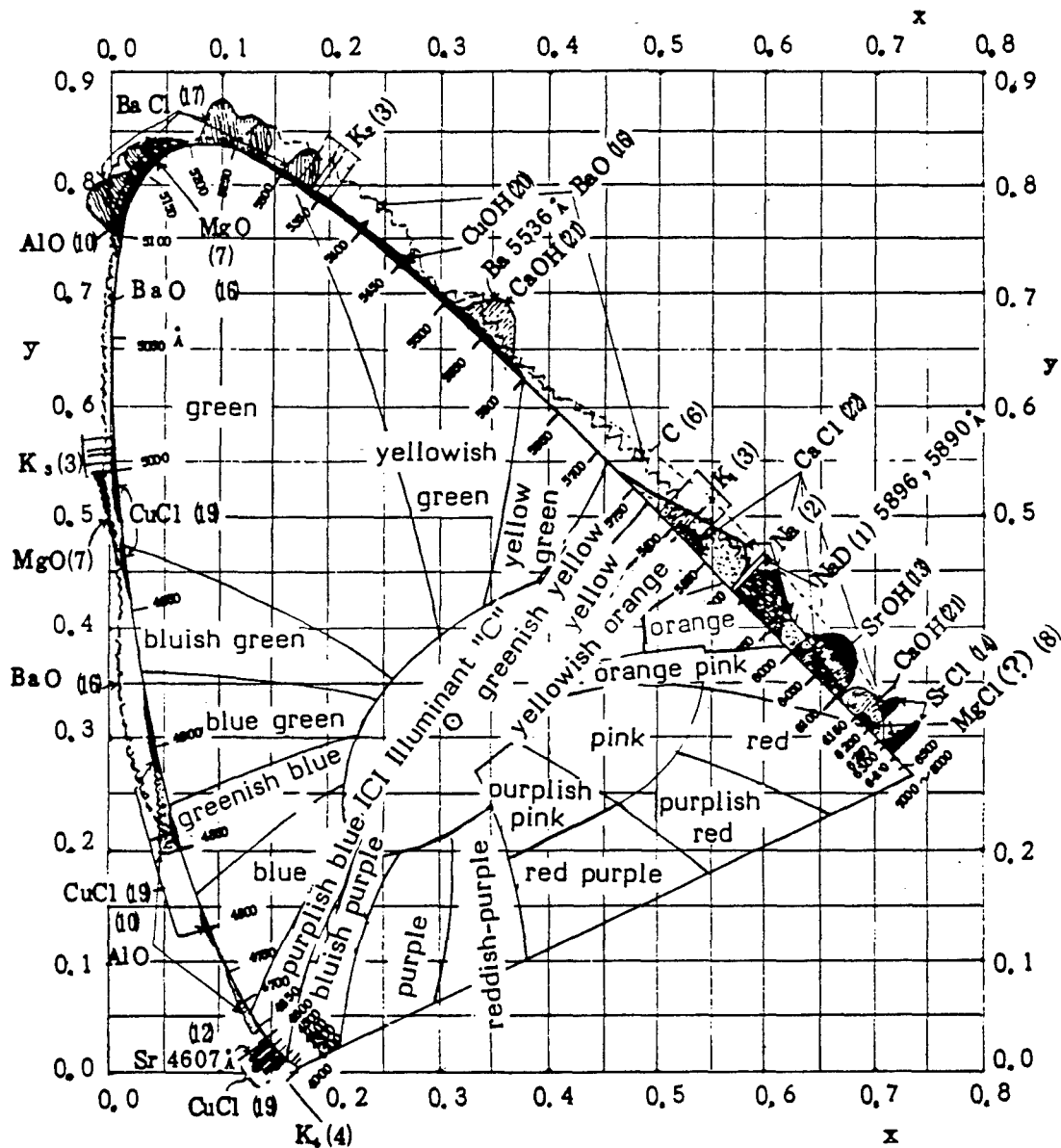


Fig. 1 -- Chromaticity diagram with flame spectra of Pyrotechnic compositions (from Shimizu¹ pg.82)

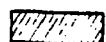

sustain combustion of the mixture and to provide heat energy to excite the color emitting molecule, a metallic fuel is normally included. These metallic fuels include magnesium, aluminum, and occasionally zirconium. These fuels, in finely ground or powder form are very reactive to the presence of an oxidizing agent, such as the oxygen present in the oxidizer salt. Above a certain temperature, the ignition temperature, the oxidizer decomposes to releasing oxygen, which then reacts quickly with the metallic fuel in the mixture, in an exothermic reaction.

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An oxidizer and metallic fuel alone, however, do not make a practical pyrotechnic for the purposes of producing colored light. The reaction is too energetic, consuming all materials in one big puff of white light -- white light being the characteristic output of MgO, for example. In the case of Strontium Nitrate and Magnesium, a chlorine donor must be provided for in the mixture so that SrCl can form in the flame. In addition, the flame must be cooled so that the white light of MgO does not overpower the desired red light, and the reaction rate must be mitigated so that the mixture has an appreciable burn time. To achieve this, an organic fuel, containing for the most part chlorine, is also provided for in the mixture. Polyvinylchloride (PVC -- $\text{CH}_2\text{:CH.Cl}$) is a typical ingredient in colored light for this purpose.

To further reduce the undesirable white light output resulting from the metallic fuel reaction, other organic fuels are helpful, as well as the presence of a small amount of unique oxidizer salts. Excess chlorine in the mixture will force the magnesium to react with chlorine and less so with oxygen. Since MgCl reactions are invisible, less white light output is realized. To this end, perchlorate ($-\text{ClO}_4$) and chloride ($-\text{ClO}_3$) oxidizers as well as high chlorine content organic fuels such as hexachloroethane (C_2Cl_6) are useful. Some organic fuels, such as shellac ($\text{C}_{16}\text{H}_{26}\text{O}_4$) contain their own oxygen supply, as well as hydrogen which produces a colorless flame, and sustains combustion without the presents of a metallic fuel. A reducing agent in the mixture can also reverse the MgO reaction limiting the presence of that molecule in the plume. MgO will react with carbon to produce Mg gas and carbon monoxide without visible light output. Oxidizers with the reducing carbon atom are the oxalates ($-\text{C}_2\text{O}_4$) and carbonates ($-\text{CO}_3$). Dechlorane ($\text{C}_{10}\text{Cl}_{12}$) is a high carbon organic fuel, which also has high chlorine content as well. The carbonates and oxalates are less reactive, in the same sense that organic fuels cool the flame, reduce energy output, and affect burn rate. Therefore, judicious proportions of each should be used or the flame may not ignite or sustain desired combustion. Figure 2 shows ignition and burning tradeoffs for a typical pyrotechnic composition based on the proportions of oxidizer, metallic fuel, and organic fuel.

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-  = area of most beautiful and practically useful flame color.
-  = unburnable region.

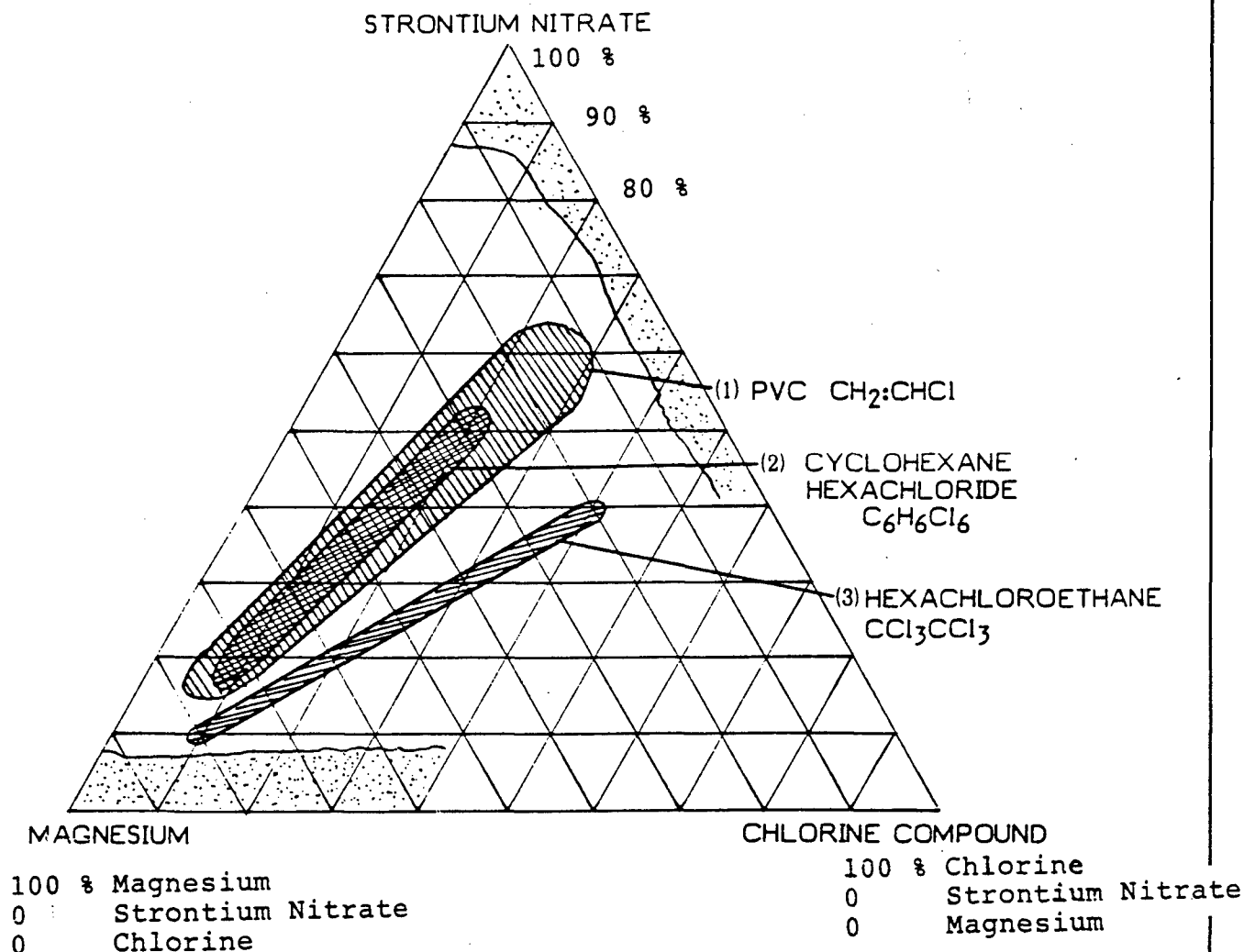


Fig 2 -- Useful regions for red flame color using strontium nitrate as an oxidizer
(Shimizu¹ pg. 89)

2. Application of the Theory to the Development of Alternate Color Tracer Formulations for 7.62mm Ball Ammunition

Developing alternate color tracer formulations builds upon the practical nature of the colored flame theory we have discussed. However, packaging restrictions placed on tracers within the base of the bullet are demanding, and can limit the

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performance. In the case of the caliber 7.62mm bullet, the tracer should provide visible light to an effective range of about 900 yards which translates into a burn time of approximately 1.6 seconds. Ideally, the tracer formulation should maximize its light energy output during this burn time so that excess tracer volume within the bullet has not been wasted. Development of such an optimized tracer formulation is outside the scope of this task. However, factors affecting tracer performance were considered when preparing and testing candidate formulas so that a good feel for the optimizing parameters could be developed. Oxidizer-fuel ratio is one of the major parameters affecting tracer burn time and intensity. Aside from too much of one or the other making the tracer mixture un-ignitable or unable to sustain combustion, within workable proportions, more organic fuel increases the burn time and decreases the intensity by cooling the flame, while more metallic fuel to oxidizer gives the opposite effect by generating greater heat output. Therefore, there can be several competing reactions within the combustion.

Since the formulas are at least three component mixtures, understanding the relative proportions of each active ingredient is important. One only has 100% of the weight of the mixture to partition among the constituents. Therefore, knowledge of the percent weight of chlorine, carbon, oxygen, or color emitting species within each material is important. Table 1 presents the relative oxygen content for oxidizers considered in this task, grouped as applied to their primary tracer color formulation. Table 2 presents organic fuels and the content of their available chlorine and carbon reducing agent.

The color emitting oxidizers in Table 1 were chosen based on their primary spectra output as shown in Figure 3-a,b,c, namely the strontium, barium, and sodium spectra. The desired spectra band for the yellow tracer formulation is .5770-.5830 microns. As shown in Figure 3-c, atomic sodium emits generously within this bandwidth. One of the unique advantages of the yellow sodium flame is that it is generated by the excitation of atomic sodium as opposed to a sodium containing molecule. Therefore, maintaining a cooler flame temperature is not a requirement, since there is no molecule to breakdown at high temperature. The hotter is the flame, the greater the intensity of yellow light output. One only needs to avoid too much heat which will generate white light from black body emissions.

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Table 1 -- Oxygen Content of Color Emitting Oxidizers

Red

Oxidizer		Molecular Weight	% Oxygen
Strontium Nitrate	$Sr(NO_3)_2$	212	45
Strontium Peroxide	SrO_2	120	27
Strontium Oxalate	SrC_2O_4	176	36
Lithium Nitrate	$LiNO_3$	69	70

Green

Barium Nitrate	$Ba(NO_3)_2$	261	37
Barium Peroxide	BaO_2	169	19
Barium Oxalate	BaC_2O_4	225	28
Barium Chlorate	$Ba(ClO_3)_2$	304	32

Yellow

Sodium Oxalate	$Na_2C_2O_4$	134	48
Sodium Nitrate	$NaNO_3$	85	56
Sodium Perchlorate	$NaClO_4$	122	52

Infrared

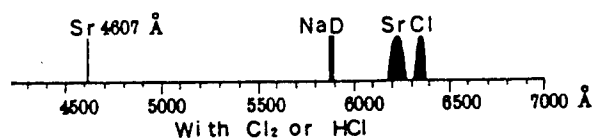
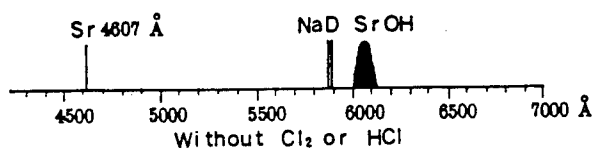
Potassium Nitrate	KNO_3	101	48
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Table 2 -- Chlorine/Carbon Content of Organic Fuels

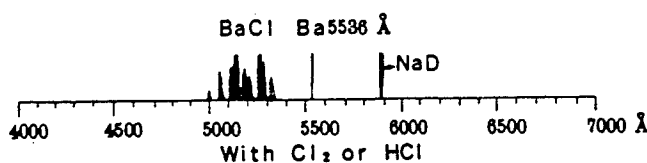
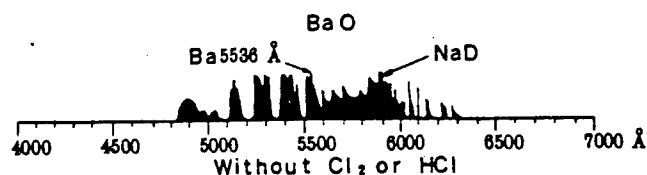
Cl/C Donor		Molecular Weight	% Cl	% C
Shellac	$C_{16}H_{26}O_4$	266	0	72
Hexachloroethane	C_2Cl_6	237	90	10
PVC	CH_2CH_2Cl	63	56	38
Dechlorane	$C_{10}Cl_{12}$	545	78	22

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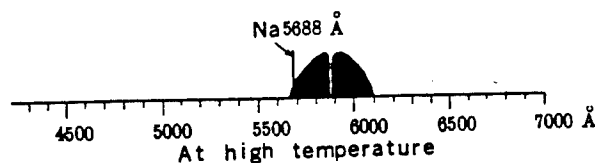
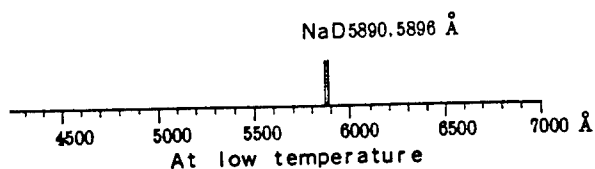
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3(a) Strontium Spectra



3(b) Barium Spectra



3(c) Sodium Spectra

Figure 3 a,b,c (Shimizu² pg. 59-62)

The desired spectra for green is .4925-.5725 microns, which is broadly covered by BaO, and covered in the lower end of the spectrum by BaCl. BaO will result in a mixture containing no Chlorine or hydrogen chloride gas. Therefore, the tracer mixture should not contain an organic fuel or oxidizer containing chlorine. This will then require that the undesirable white light of the MgO reaction is mitigated solely by the reducing

Shimizu, Dr. Takeo, Fireworks, The Art Science and Technique, Pyrotechnica, 1981

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agent carbon. Although theoretically possible, it is unlikely that the flame will have acceptable color quality. For this reason, green tracer formulations concentrated on the BaCl spectrum.

The strontium spectra is dominated by the strontium hydroxide band, without Cl_2 or HCl, and the strontium chloride band, with Cl_2 or HCl in the flame. As with the Barium spectra, generating red light by the formation of SrOH is less practical than SrCl . However, both bands are below the desired red tracer spectrum of .6500-.6900 microns, SrCl less further below than SrOH . The decision was made to test a strontium chloride based tracer mixture anyway, since there may be significant spill-over into the upper wavelengths, and no alternative could be identified. Fortunately, this was the case. However, it raises the question of whether light intensity at the SrCl wavelengths would have been significantly greater than the measured intensity at the desired wavelength of the tracer.

The infrared tracer formulation development presented unique requirements not generally addressed by the pyrotechnic community at large. Therefore, an hypothesis concerning the formation of purely infrared emissions, without the presence of visible light, was developed based on black body radiation theory, and general pyrotechnic chemistry. Figure 4 presents blackbody radiant intensity with respect to temperature. The requirement was for the tracer to maximize output at the 1.50-2.50 micron region, which can be estimated to be within a temperature range of approximately 1300 K to 1200 K, or about 1000 to 900 C, roughly.

Although this temperature range may be casually interpreted to be characteristic of a very hot flame, the opposite is actually true with respect to pyrotechnic formulations. Figure 5 shows the temperatures of several high temperature classes of flames. The desired infrared range is significantly below the flame temperature of ordinary tracer and flare formulations. This knowledge, coupled with the understanding that visible light output is normally the smallest proportion of energy radiation during combustion, leads one to the conclusion that an effective IR tracer will be one based on a relatively cool burning tracer formulation. A cool burning flame also has the advantage that white light output generated by high temperature blackbody emissions will be minimized as will colored light output, which must have a certain minimum heat energy to be activated as well.

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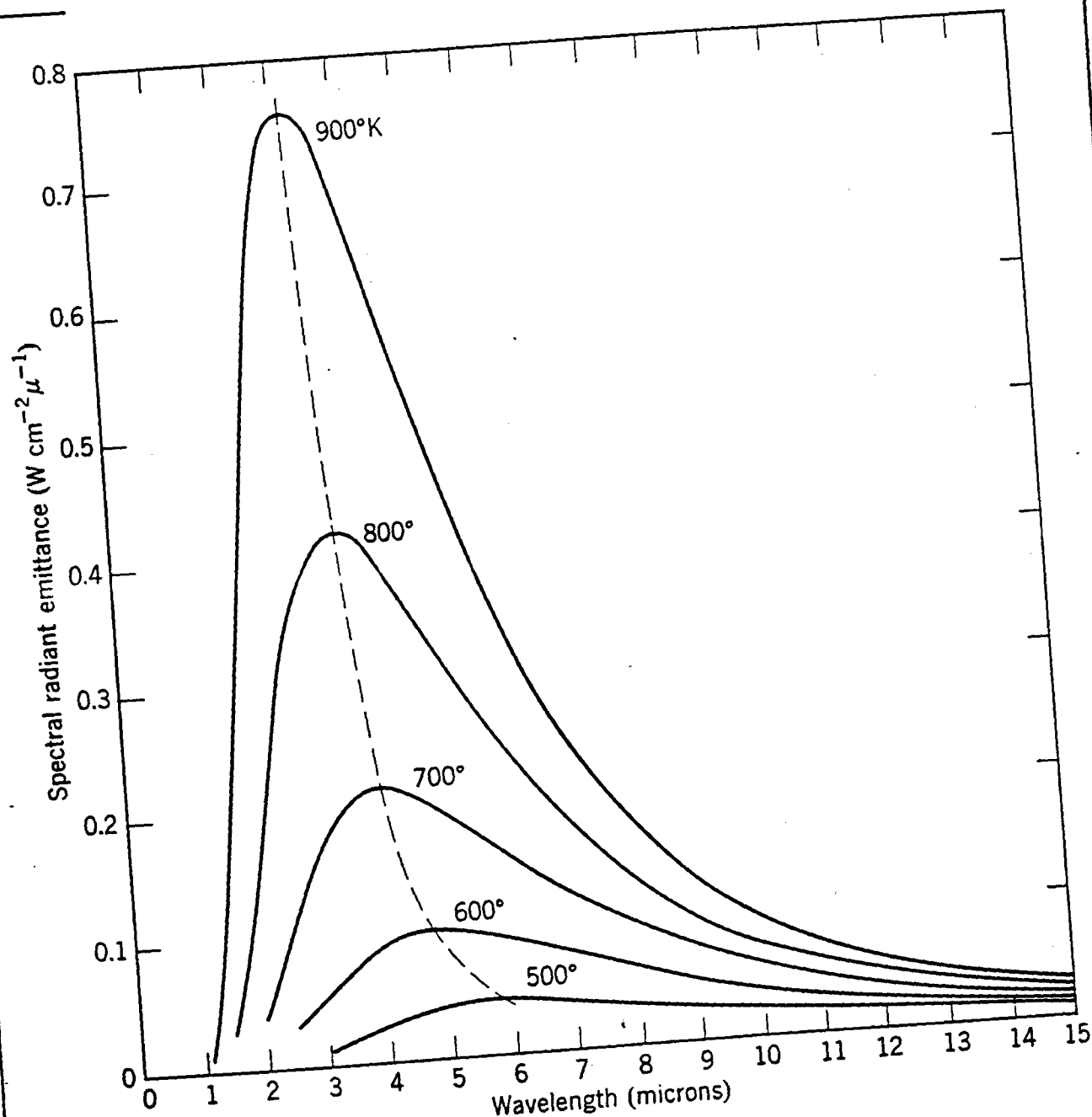


Figure 4 -- Blackbody Radiant Emittance as a Function of Wavelength and Temperature

Cool burning tracer formulations will be those which contain no metallic fuel, but rather suitable organic fuels. Figure 6 shows the flame temperature of a potassium nitrate and shellac formulation, which is approaching the desired cooler temperature

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range for the IR tracer requirement. For this reason, potassium nitrate is a candidate IR tracer oxidizer, even though at high temperatures its emissions are characterized by intense white light.

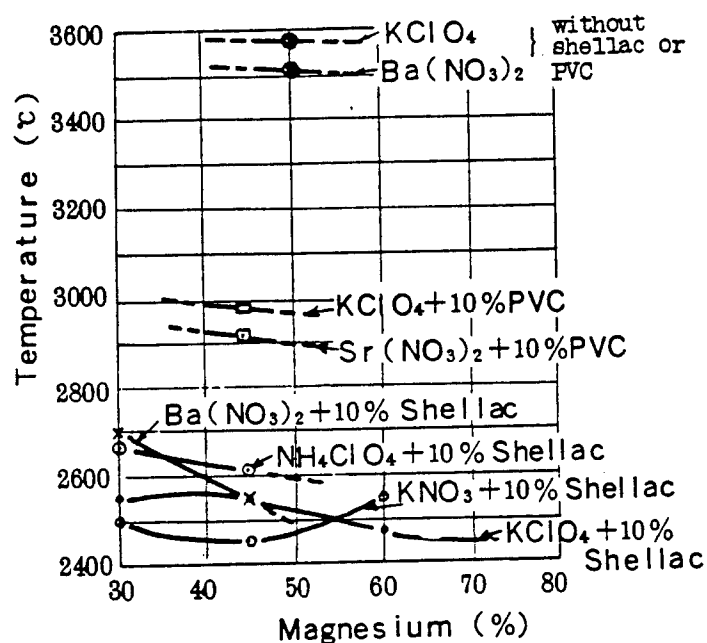


Figure 5 -- Temperatures of High Temperature Class Flames (Shimizu²)

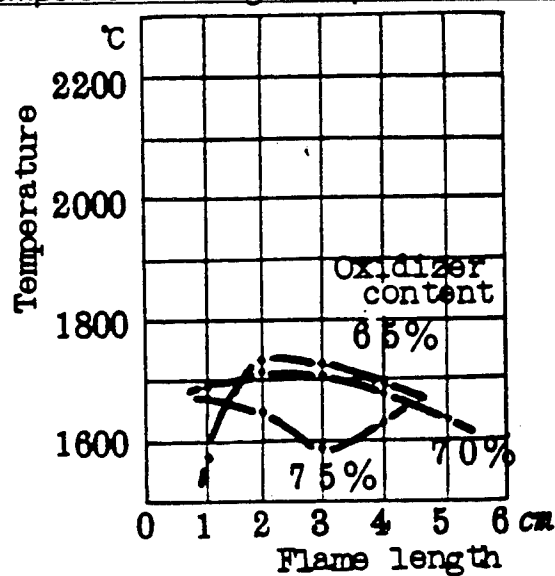


Figure 6 -- Flame Temperature for Potassium Nitrate and Shellac (Shimizu²)

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Based on this information, tracer formulations were developed which would maximize emission within the desired spectral band, enhance color quality through reduction of unwanted light (primarily white), and maximize tracer efficiency by achieving a burn time of approximately 1.6 seconds.

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Section 3

Color Perception, Radiometry, and Tracer Color Properties

There are several perception related obstacles that affect the development of alternate tracer colors. Fortunately they are both correctable to a degree. The first is the dearth of quantitative spectral and power data on existing tracer formulations. The development of these tracers was completed a number of years ago, in a very ad hoc way, and it is difficult to understand exactly what their characteristics are and how they will perform under different situations. The second issue is the uncertainties relating to how the human eye and the optic nervous system perceive different colors, and the fact that different individuals view colors differently.

Since tracers are meant to be viewed by human observers, the transfer function of the viewer (determined primarily by his ability to distinguish different colors) is ultimately the most important factor of all. However, human color perception is very subjective and difficult to quantify. In addition, the mechanism for distinguishing colors is different in daylight and darkness. The retina of the eye contains two types of photo-sensitive elements - "cones" and "rods", with the cones predominating when the eye is adapted to daylight and the rods predominating when the eye has adapted to lower background illumination levels. The daylight response is known as photopic eye response, and the night vision is referred to as scotopic eye response. Naturally, the scotopic eye response is more sensitive, but it is important to understand that scotopic color perception is poorer. That is - the eye response is more sensitive at night, but the ability to separate colors is poorer. However, the eye is able to see the longer red wavelengths better at night. Figure 7, shows the relative spectral photopic and scotopic eye response of a typical human eye.

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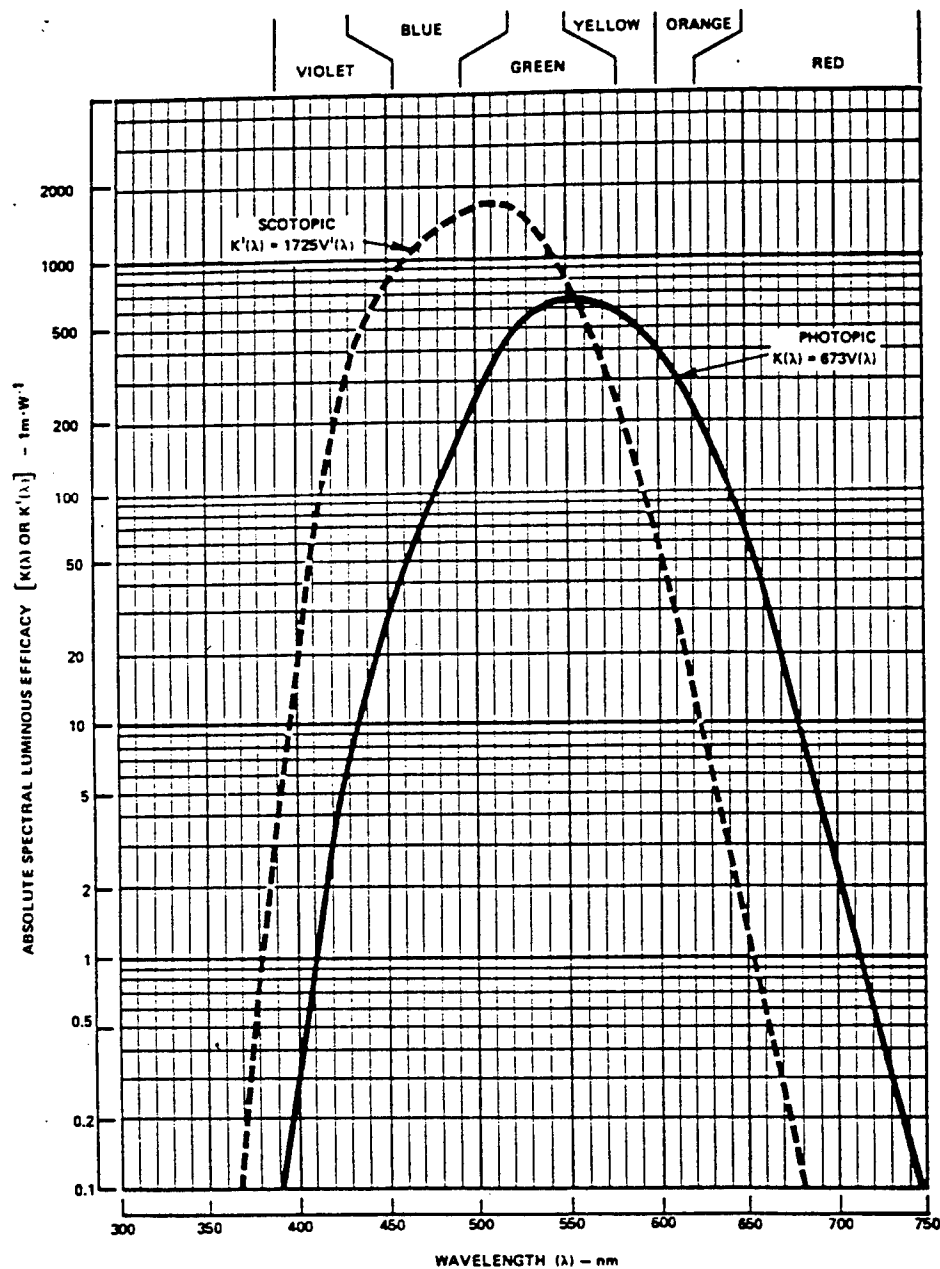


Figure 7 - Absolute Spectral Luminous Efficacy of a Human Eye*

* Reprinted from Electrooptics Handbook

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The exact, quantitative mechanics of human color vision are largely unknown, but it has been determined that the response is shared by the photosensitive elements in the eye and the brain. The leading theory is the trichromatic theory, which holds that the retina of the eye consists of a mosaic of three different receptor elements. Each element responds to a specific wavelength, corresponding to blue, green and red light. These three elements, which appear to overlap considerably in responsivity, are separately connected through nerves to the brain, where sensory perception of color is derived by the brain's analysis of the relative stimulus from each of the elements. It is the overlap, that may be different in different individuals, that results in uncertainty in color perception.

Color is perceived as a conscious sensation in terms of at least three major subjective attributes: luminance (or brightness), hue (the distinction between redness, blueness, and yellowness), and saturation which results from color purity and freedom from dilution by spurious white light. Therefore, there are uncertainties in the meaning of color perception. These uncertainties mean that the only way to meaningfully describe tracer performance is by specifying the spectral bandwidth, the output power (in watts per steradian), and the required burn duration. These parameters then need to be related to visual perception in a useful way, and this can be accomplished by firing a statistically meaningful number of rounds under different conditions and having a variety of individuals observe the colors under different conditions. Regardless of how many rounds are fired, it is essential to develop a database of tracer formulations that can then be used to compare different tracers, confirm specified operating parameters, and perform lot checks during manufacturing. This is a meaningful compromise to quantitatively specifying hue and saturation, as well as out-of-band light energy.

This task order was prepared in a scientifically consistent manner in that spectral bands as well as visually perceived colors were specified. This permitted the required quantitative measurements to be made and compared to visual perception of the specified colors.

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Looking at optical bands, and correlating to visual perception can be ambiguous, however a reasonable summary of the specified bands and perceived colors is as follows:

GREEN: .4925 - .5725 microns

This spectral region is large, and covers the green and part of the yellow region of the spectrum. Because of the large portion of the spectrum that is included, the amount of light energy emitted can be expected to be large.

YELLOW: .5770 - .5830 microns

The specified spectral width for this region is very narrow. The color associated with this region is yellow, leaning toward the orange.

RED: .6500 - .6900 microns

This region is at the longer part of the red spectral region, and is associated with a very deep red.

DIM TRACE: 1.50 - 2.50 microns

This is in the infrared portion of the spectrum and is completely invisible to the unaided human eye. The only way to view energy in this spectral region is with a detector that is designed to be sensitive to near infrared energy.

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Section 4

Tracer Fabrication

The fabrication of the tracer formulations was performed using a set of tooling that was designed and constructed specifically to result in a tracer pellet that could be pressed into the cavity of the 7.62mm ball tracer round. The design of this tooling is derived from identical tooling that we have previously designed and used in the fabrication of .50 caliber tracers.

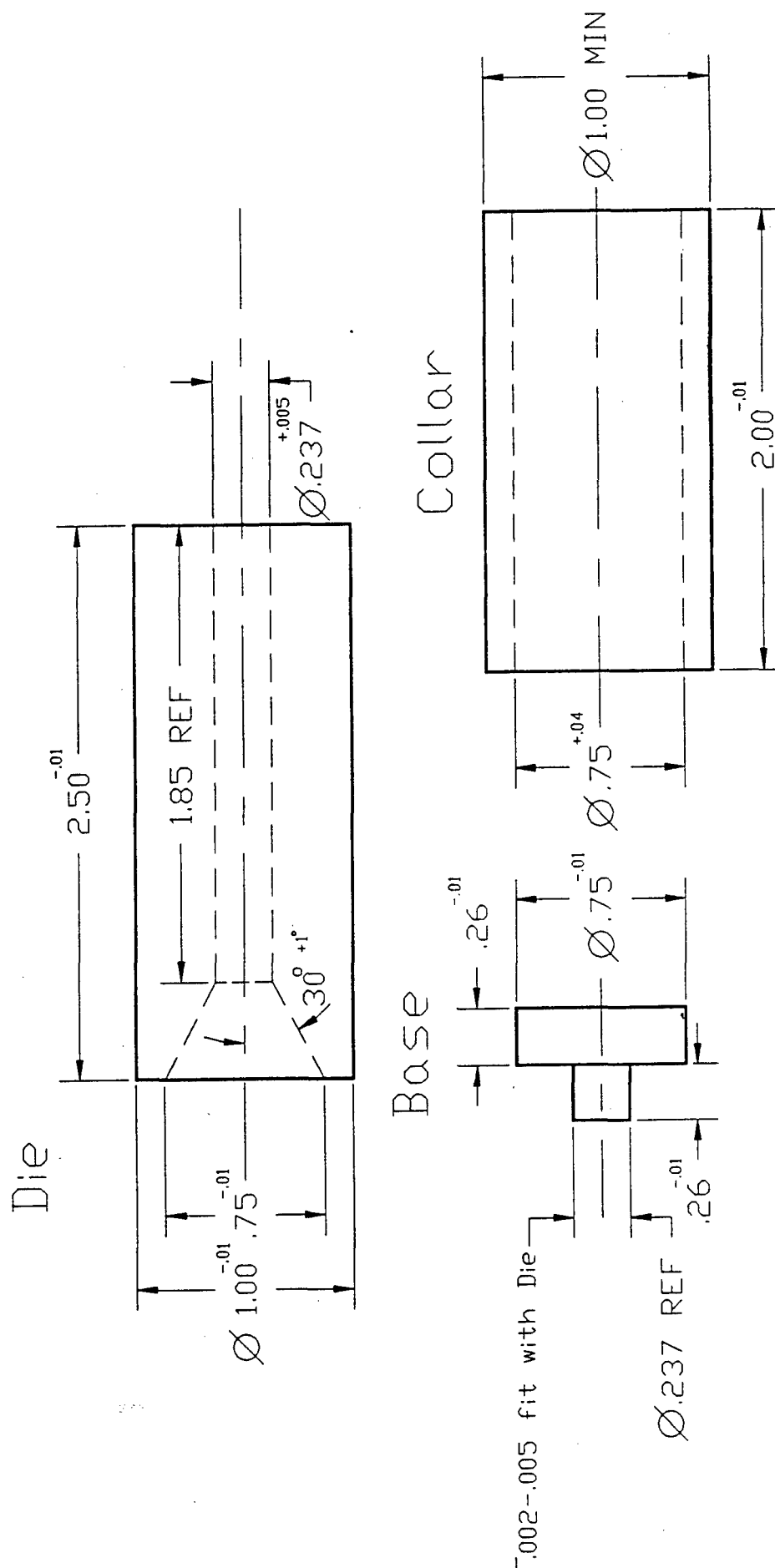
All oxidizers and organic fuels are purchased in one pound lots and individually ground to a fine powder using a hand mortar and pestle and passed through a #120 mesh sieve. After grinding, they are individually bulk stored in airtight containers with approximately 1000 grains (65 grams) of powder in each. The magnesium fuel has been purchased to a specification of passing a #325 mesh sieve, which was more than sufficient to require no further material processing prior to mixing.

For purposes of economy, since numerous formulations would be mixed, tested, and perhaps discarded, it was found that best results were obtained by mixing no more and no less than 50 grains of formula at any one time. This amount provides for ease of mixing and tumbling, with excellent uniformity and minimum risk of spillage affecting quality control. Constituent materials are individually weighed to the nearest 0.1 grain, and tracer charging typically requires 8 grains of mixture for a 7.62mm cavity, depending on density.

Tracer charging is performed by a process that first forms a pellet of the mixture. Then the compacted pellet is lightly pressed into the base of a steel slug containing an internal tracer cavity of dimensions equal to that of the 7.62mm tracer projectile cavity. Figures 8(a) and 8(b) show the pelletizing tooling used in this task. Due to the bulk of the un-compacted powder, efficient compaction of the mixture into

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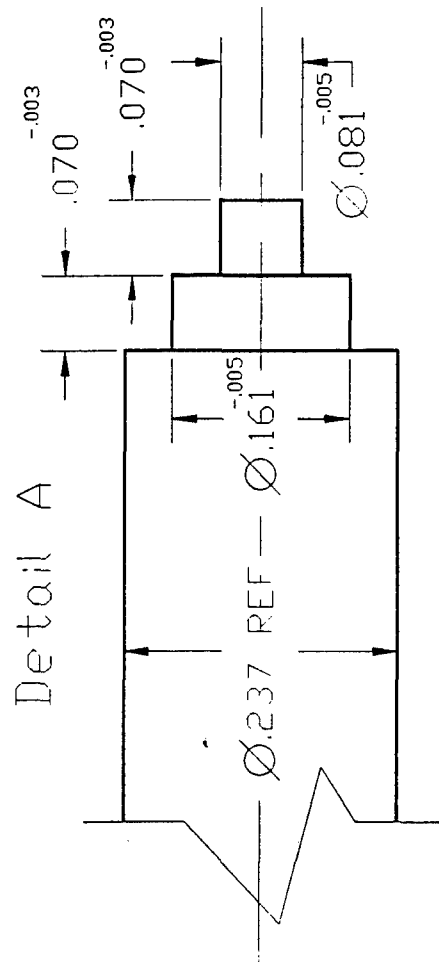
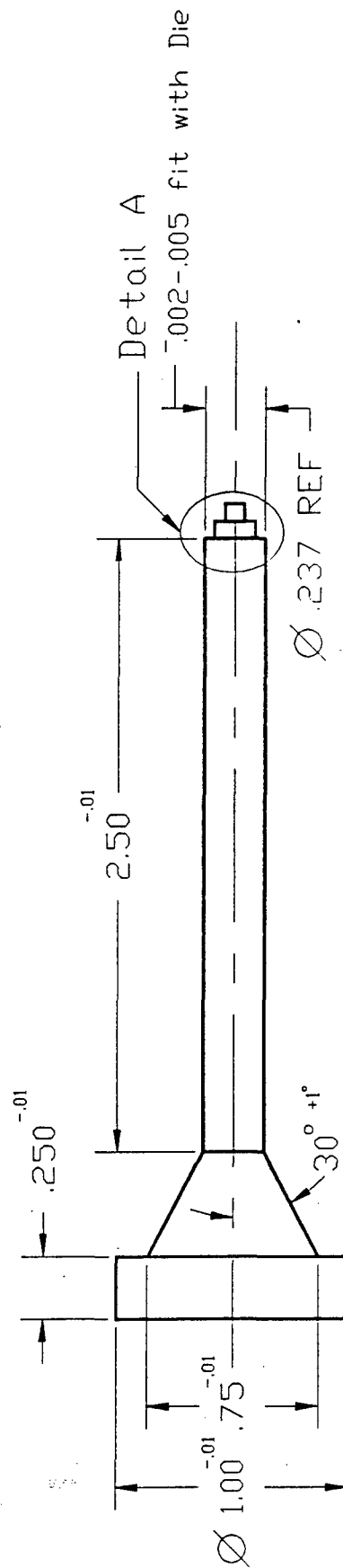
Figure 8(a) - Die and collar Assemblies



1. Die and Base material as convenient, non-corrosive or passivated, min yield 150 ksi tensile.
2. Collar material non-specific convenient tube stock.

Figure 8(b) - Punch Assembly

Punch



1. Material as convenient, non-corrosive or passivated, min yield 150 ksi tensile

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the base of the slug was not practical. To alleviate this, an upright die is fitted with a base plug and then filled with the tracer mixture in powder form. A punch is then inserted into the mouth of the die and the entire assembly compacted using a laboratory press. To extract the resulting tracer pellet, a collar is placed below the base and the punch continues to ram the base and pellet out in the same direction as it was compacted. A stepped contour is provided at the tip of the punch to give an internal cavity at the tracer mouth of greater surface area so that ignition may be more reliable. In practice, the compacted pellet remains rigidly affixed to the end of the punch, so that the bullet was immediately charged prior to extracting the punch from the die. The tracer formulas were compacted to an average pressure of 40,000 psi.

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Section 5

Instrumentation and Measurement of Tracer Performance

5.1 General

The objective of the measurement phase of this effort has been to validate the specified parameters and characteristics of the tracer formulations. There are several important considerations that dictated the techniques that were used, and the measurements that were made.

Since the colors were specified by spectral regions, and the human eye does not distinguish colors with this level of spectral resolution, it was necessary to construct dedicated instrumentation to measure the light output in the specified bands. The spectrometer type instruments that were constructed were used in conjunction with a digital oscilloscope that displayed the absolute intensity as a function of time and recorded the data on a disc for later analysis.

In order to simulate, as closely as possible, the actual conditions under which the tracer material will burn, we constructed a 7.62mm tracer cavity, in a generic bullet-like device, that we could spin at approximately 21,000 rpm and blow air along the spin axis. It was recognized that the 21,000 rpm spin rate is lower than the rate at which the bullet spins as it exits the barrel, however we noted that the difference between the stationary burn and the spinning burn was significant, and may indicate a trend as the spin rate is increased further. At any rate, the final tests will be with the firing of bullets with the new tracer formulations.

5.2 Spectral Measurements - Visible

In order to satisfy the task order requirements, it has been necessary to measure the in-band intensity as a function of time for each of the three visible

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spectral bands. Since this data should be available for future comparison, the measurements must result in a direct electrical output, and this output then stored digitally. In order to make these measurements, a number of systems were considered, and a relatively simple spectrometer device was constructed. The heart of the device is a variable dichroic filter made by the Oriel Corporation (Model 57480). This filter discriminates light throughout the entire visible portion of the spectrum, and the wavelength region that is passed is a function of where on the filter the measurement is made. That is, one side is uniformly illuminated, and the opposite side performs a spectral decomposition. Thus, a slit that moves from one end to the opposite end can selectively pass from deep red to violet. The narrower the slit, the more monochromatic the output. For this application, a pair of masks was configured with slits as stops for each of the three spectral bands, with the width of the slit adjusted to pass exactly the desired portion of the spectrum. A large area silicon photodetector, was used to obtain an electrical signal proportional to the in-band light energy falling on the filter. The detector output is fed into an operational amplifier configured with several gain settings to adjust for the differences in output due to the large differences in the width of the spectral bands.

A schematic of the spectrometer is shown in Figure 9. In order to keep the device simple, the input surface is an acrylic diffusion lens, so that focusing optics are not required. The active area of the filter is controlled by the two opaque stops, that can be made transmissive in different filter positions, corresponding to different spectral pass-bands. The band in which light is passed is controlled by both the location and width of the slits that are cut into the stops. The silicon photodiode is placed behind a specific slit to convert the light energy to an electrical signal, and is moved as the as each band is selected. Both the center wavelength and the bandwidth can be set by adjusting the location and width of the slit. Four sets of masks have been constructed and calibrated for the three visible bands. Four filter sets were required because the specified green region is so wide that the detector could not collect all the energy without collimating optics, and the green was therefore broken into two regions, since this was simpler. The gain settings, controlled by a toggle switch, are designed to permit us to place the instrument 60 cm from the tracer, and obtain useful levels of output to feed the digital recording oscilloscope.

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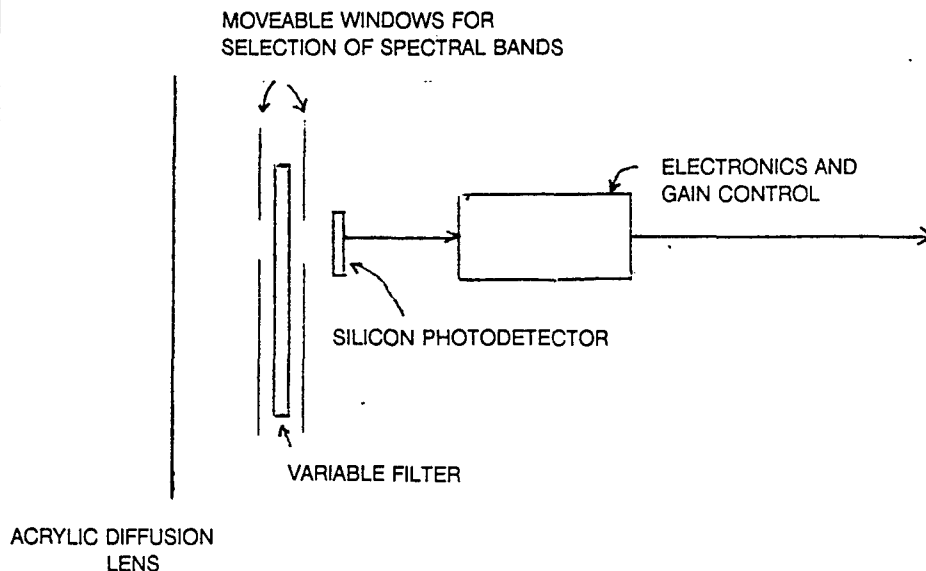


Figure 9 - Schematic of Visible Spectrometer

5.3 Instrument Calibration

In order to ensure that we would obtain repeatable and traceable results, and that we would, at some time in the future, be able to compare our results with existing tracer formulations in a quantitative way, the instrument was calibrated as precisely as possible. The method of calibrating the instrument was to position it at normal incidence and at 50cm from the calibration source with the collector fully illuminated. The calibration source was a 1000W FEL Standard of Spectral Irradiance that was calibrated by a direct irradiance transfer from a National Institute of Standards and Technology (NIST) primary standard. In addition, the filter and detector linearity were tested by taking readings with a number of neutral density filters. This test was made in Band 5, using the low gain setting. The transmissions of the neutral density filters were verified on a Lambda 3 Spectrophotometer. The spectral content of the 1000W FEL standard, and the filter calibrations are shown in Figures 10 and Table 1, respectively.

1000W FEL #91453 IRRADIANCE AT 50cm

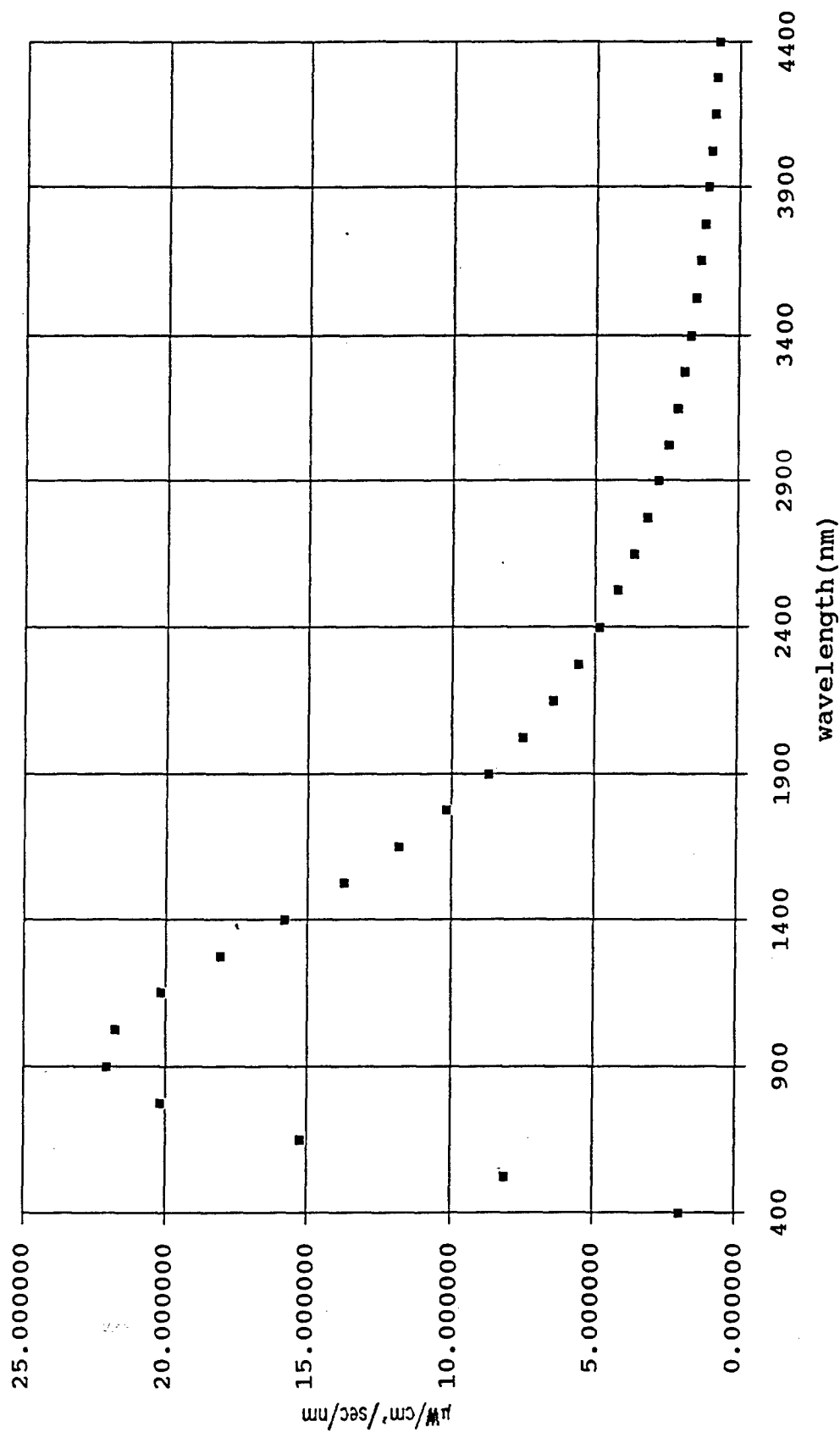


Figure 10 - Spectral Content of 1,000 watt FEL Irradiance Standard

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filter	trans.	net reading(v)	reading/trans
none	100.0%	3.71	3.71
0.3	51.7%	1.97	3.810444874
0.5	31.8%	1.15	3.616352201
1	10.9%	0.39	3.577981651
2	1.3%	0.04	3.076923077
3	0.2%	0	0

Table 1 - Calibration of Neutral Density Filters

To calculate the irradiance on the detector a table was built for each response function at 5nm intervals (at 1nm intervals for band 3) and the function was multiplied by the calibration sources spectrum and this product was numerically integrated. Each integral represents the total irradiance in each band at 50cm from the calibration source. These are shown in Tables 2 (a) - (c).

With the component calibration complete, the filters for each of the bands were adjusted to match the spectral regions that were specified. The relative response of each of the five bands, normalized to peak, are shown in Figure 11. The specified band limits are approximately 50% of peak. The final calibration was made for each gain setting separately, for each band. The calibration constants for the instrument are shown in Table 3. The actual quantity that needs to be measured is the radiance from the tracer, in watts per steradian (W/SR). The final calibration to determine the radiance considers that the active area of the tracer spectrometer is 14.9 cm², and the measurements were made 60 cm from the tracer. Therefore, the solid angle covered is .004 steradians, and the conversion from irradiance (in μ watts/square cm/volt) on the photometer surface to radiance from the tracer (in milliwatts/SR/volt) is 3.7 x [calibration factor]. This is the significant number, since the in-band radiance from the tracer is the important number that reflects as performance.

BAND 1

wl(nm)	relative response	irradiance uW/cm ² /nm	resp*irrad product
485	0.000	5.65	0.00
490	0.362	5.92	2.14
495	0.495	6.20	3.07
500	0.764	6.48	4.96
505	0.875	6.77	5.92
510	0.953	7.05	6.72
515	0.979	7.34	7.19
520	1.000	7.64	7.64
525	0.946	7.93	7.50
530	0.811	8.23	6.67
535	0.603	8.53	5.14
540	0.155	8.82	1.36
545	0.000	9.13	0.00
sum=			58.31
sum*5nm=			291.55

BAND 2

wl(nm)	relative response	irradiance uW/cm ² /nm	resp*irrad product
520	0.000	7.64	0.00
525	0.128	7.93	1.01
530	0.482	8.23	3.96
535	0.790	8.53	6.74
540	0.939	8.82	8.29
545	1.000	9.12	9.12
550	0.979	9.43	9.23
555	0.961	9.73	9.34
560	0.912	10.03	9.14
565	0.816	10.33	8.43
570	0.645	10.63	6.86
575	0.367	10.93	4.01
580	0.136	11.22	1.52
585	0.000	11.52	0.00
sum=			77.65
Int.=sum*5nm=			388.25

Band 3

wl(nm)	relative response	irradiance uW/cm ² /nm	resp*irrad product
575	0.000	10.93	0.00
576	0.250	10.99	2.74
577	0.653	11.05	7.21
578	0.898	11.11	9.98
579	1.000	11.17	11.17
581	0.999	11.28	11.27
583	0.932	11.40	10.63
585	0.614	11.52	7.08
586	0.253	11.58	2.92
587	0.261	11.64	3.03
588	0.000	11.70	0.00
SUM=			66.02
SUM*1nm=			66.02

Band 4

wl(nm)	relative response	irradiance uW/cm ² /nm	resp*irrad product
585	0.000	11.52	0.00
590	0.107	11.82	1.27
595	0.357	12.11	4.33
600	0.606	12.40	7.51
605	0.779	12.69	9.89
610	0.913	12.97	11.85
615	0.982	13.26	13.01
620	1.000	13.54	13.54
625	0.929	13.81	12.83
630	0.840	14.09	11.83
635	0.734	14.36	10.54
640	0.551	14.62	8.07
645	0.324	14.89	4.82
650	0.093	15.15	1.41
655	0.000	15.40	0.00
SUM=			97.79
SUM*5nm=			488.94

Band 5

wl(nm)	relative response	irradiance uW/cm ² /nm	resp*irrad product
640	0.000	14.62	0.00
645	0.103	14.89	1.54
650	0.393	15.15	5.95
655	0.615	15.40	9.47
660	0.786	15.65	12.31
665	0.916	15.90	14.56
670	1.000	16.14	16.14
675	0.887	16.38	14.52
680	0.833	16.61	13.83
685	0.652	16.84	10.98
690	0.344	17.06	5.87
695	0.045	17.28	0.77
700	0.000	17.50	0.00
SUM=			88.99
SUM*5nm=			444.96

Table 2 - Total Irradiance in Each Band

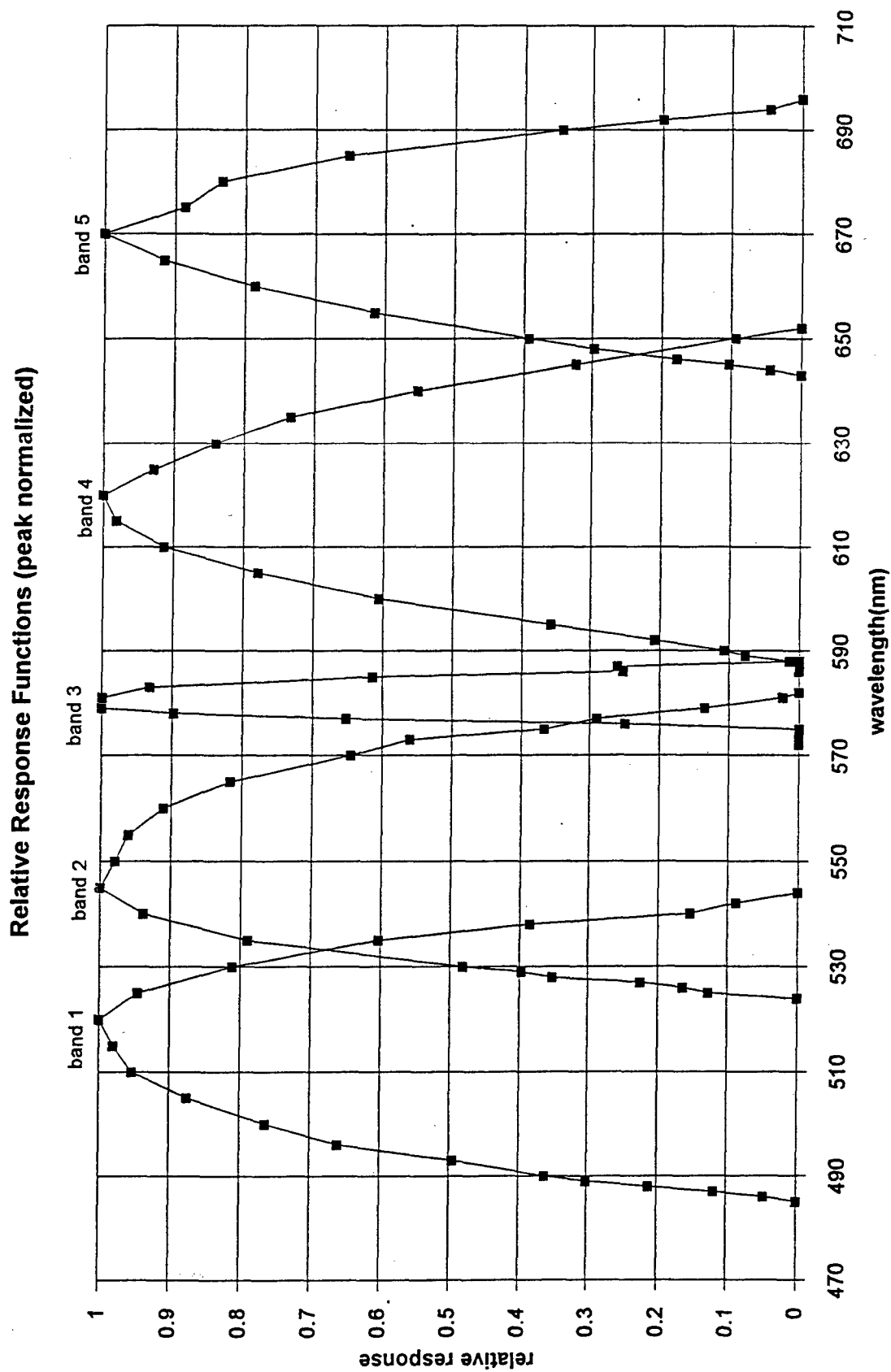


Figure 11- Relative Response Functions

Calibration Certificate for Variable Spectrometer

instrument model: VSP-1000

serial #: 100

calibration date: 4/4/93

calibration source : 1000W FEL lamp #91453

irradiance units: uWatts/cm²calibration factor units: uWatts/cm²/volt

Low Gain Setting

BAND#	LIGHT V	DARKV	NET V	ND#	ND TRANS	INTEGRATED IRRADIANCE	INTEGRATED IRRADIANCExND	CAL FACTOR IRRADIANCE/VOLTS
1	1.11	0.00	1.11	0	100.00%	291.56	291.56	262.67
2	1.91	0.00	1.91	0	100.00%	388.25	388.25	203.27
3	0.43	0.00	0.43	0	100.00%	66.02	66.02	153.53
4	3.85	0.00	3.85	0	100.00%	488.94	488.94	127.00
5	3.67	0.00	3.67	0	100.00%	444.96	444.96	121.24

Mid Gain Setting

BAND#	LIGHT V	DARKV	NET V	ND#	ND TRANS	INTEGRATED IRRADIANCE	INTEGRATED IRRADIANCExND	CAL FACTOR IRRADIANCE/VOLTS
1	5.38	0.00	5.38	0.3	51.70%	291.56	150.74	28.02
2	5.71	0.00	5.71	0.5	31.80%	388.25	123.46	21.62
3	3.92	0.00	3.92	0	100.00%	66.02	66.02	16.84
4	3.82	0.00	3.82	1	10.90%	488.94	53.29	13.95
5	3.60	0.00	3.60	1	10.90%	444.96	48.50	13.47

High Gain Setting

BAND#	LIGHT V	DARKV	NET V	ND#	ND TRANS	INTEGRATED IRRADIANCE	INTEGRATED IRRADIANCExND	CAL FACTOR IRRADIANCE/VOLTS
1	5.00	0.00	5.00	1+3	5.64%	291.56	16.43	3.29
2	1.90	0.00	1.90	2	1.30%	388.25	5.05	2.66
3	3.26	0.00	3.26	1	10.90%	66.02	7.20	2.21
4	4.31	0.00	4.31	2	1.30%	488.94	6.36	1.47
5	4.14	0.00	4.14	2	1.30%	444.96	5.78	1.40

calibration notes:

1. Voltages are recorded with the detector positioned at 50cm from the calibration source ,at normal incidence and with the collector completely illuminated.
2. The Integrated Irradiance is the total lamp irradiance at 50cm in each spectral band.
3. Neutral density filters were used for some of the readings. The filters were calibrated with a Lambda 3 Spectrophotometer and their transmission values appear above. These values were used as multiplication factors to calculate the actual irradiance at 50cm.
4. The calibration factors are calculated by multiplying the integrated irradiance and the neutral density transmission and dividing that by the net voltage reading. This factor is used to determine the irradiance of a source by multiplying it by the net voltage reading.

Table 3 - Calibration Constants for Each Gain Setting and Band

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5.4 Measurements - Infrared

For the infrared tracer measurements, a separate instrument was constructed. This instrument consisted of an in-band filter and a photoconductive detector. The detector was connected in a bridge circuit with a bank of batteries totaling 27 volts. The same FEL 1,000 watt calibrated lamp was then used with a series of neutral density filters to calibrate the entire device, so that the calibration could be again traceable to a NIST standard.

5.5 Instrument Calibration - Infrared

The infrared relative response was derived by putting both a low pass and a high pass filter in front of the detector, and the measured relative response, normalized to peak is shown in Table 4. The fact that this was put together with readily available components, caused a slight deviation from the specified spectral band.

The results of the calibration are shown in Figure 12. The receiving aperture is a circle with a diameter of 1.3 cm, and the receive area is therefore 1.3 cm^2 . The distance from the tracer to the sensor was 20 cm, and the included solid angle was, therefore, .003 steradians. Since the calibration factor is $0.0017 \text{ v}/\mu\text{watt}/\text{cm}^2$, and the area is 1.3 cm^2 , the factor is $445 \mu\text{W}/\text{volt}$. $445/.003 = 0.15 \text{ watt}/\text{SR}/\text{Volt}$. The infrared instrument has one calibration, since only one band is included.

IR Detector Calibration

WL	Tfilter	det resp	4.128E+10	Relative	Cal Lamp	Rel Resp Fn
			Tfilter*det resp	Resp. function	Output	*Lamp Out
1500	0	7.2E+10	0	0	14.1128081	0
1625	0.025	8E+10	2000000000	0.04844961	12.1621242	0.58925021
1750	0.1	8.3E+10	8300000000	0.20106589	10.445893	2.10031279
1875	0.2	9E+10	1.8E+10	0.43604651	8.96444612	3.90891546
2000	0.33	9.3E+10	3.069E+10	0.7434593	7.69942095	5.72420613
2125	0.42	9.8E+10	4.116E+10	0.99709302	6.62539877	6.60613889
2250	0.43	9.6E+10	4.128E+10	1	5.71584721	5.71584721
2375	0.46	8.2E+10	3.772E+10	0.91375969	4.94591538	4.5193781
2500	0.43	6E+10	2.58E+10	0.625	4.2935535	2.68347094
2625	0.325	4E+10	1.3E+10	0.31492248	3.73977866	1.17774037
2750	0.16	2.2E+10	3520000000	0.08527132	3.26853366	0.27871217
2875	0.01	1.3E+10	130000000	0.00314922	2.86637587	0.00902686
3000	0	7000000000	0	0	2.52211685	0

Integrated Irradiance= sum= 33.3129991
 125*sum= 4164.12489

Conditions at calibration:	
Light Voltage=	-6.24 v
Dark Voltage=	0.95 v
Net Voltage=	-7.19 v
Integrated Irradiance=	4164.1249 $\mu\text{Watts/cm}^2$
Calibration Factor=	-0.00172665 V/ $\mu\text{Watts/cm}^2$

Table 4- Infrared Detector Calibration Data

IR Detector Relative Response (Peak Normalized)

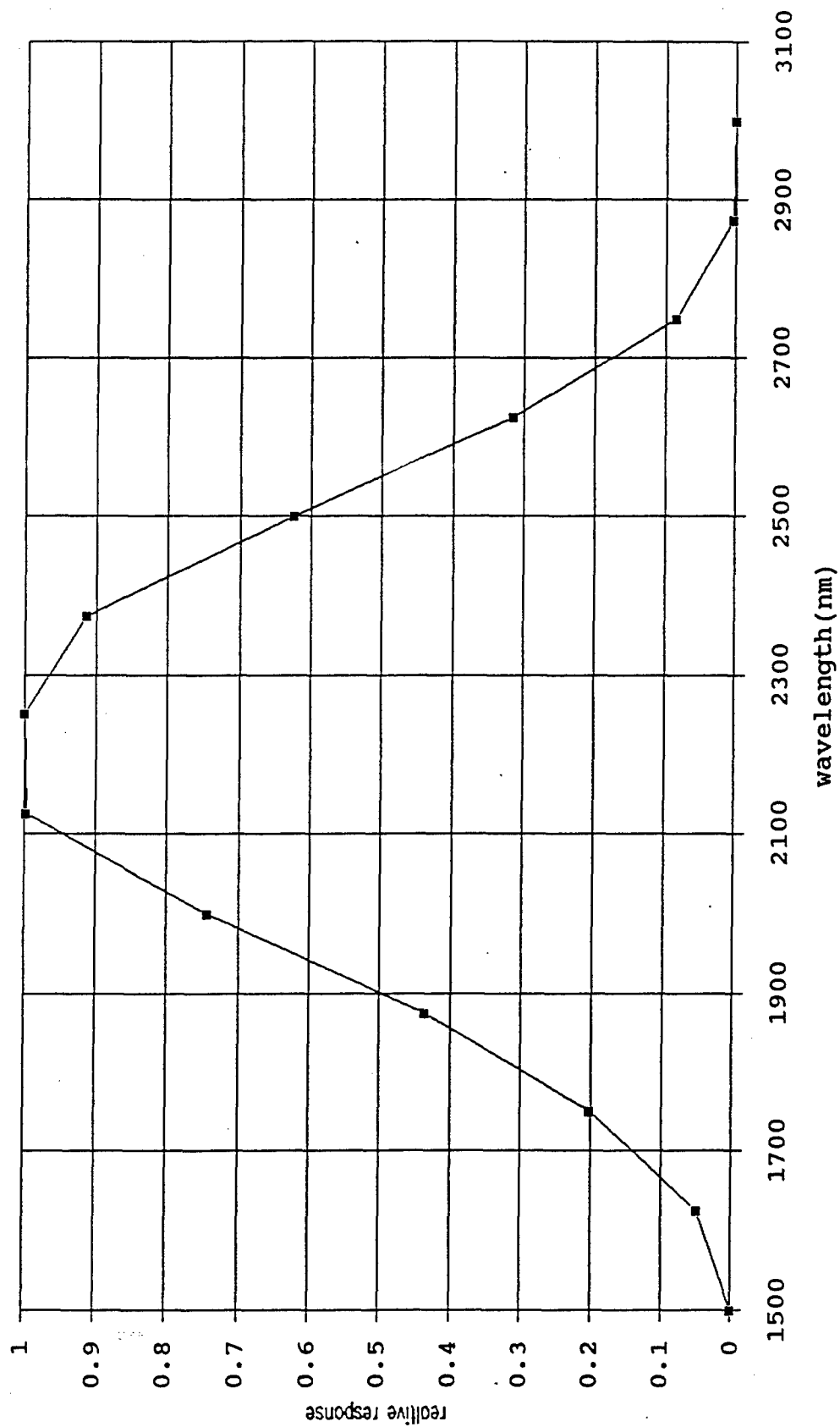


Figure-12 - Infrared Detector Peak Response Function

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Section 6

Observations and Results for Each Color

6.1 General

In order to make the desired measurements for each of the formulations that was selected, the tracer slugs were positioned below a ventilation hood and ignited with a propane torch. Data was collected on their spectral emissions for both static and spinning (with air blowing by) conditions. The tracer slugs were spun to a rate of 21,000 rpm (revolutions per minute) using a compressed air driven drill. This spin rate is significantly less than the average 170,000 rpm that the projectile realizes in flight. However, even at 21,000 rpm a clear difference in performance was observed. Spectral emissions were measured for the visible color producing tracer formulas at a constant distance of 24 inches from the detector. Infrared emissions were measured at a distance of 8 inches due to the much reduced output of these formulas and the lower sensitivity of the detector. In order to provide consistent, repeatable, and useful results, radiant intensity is the parameter that was measured and recorded. The data that was recorded for each of the four specified bands is the in-band radiant intensity (in watts per steradian) as a function of time. This is a universal quantity that can be used as a quantitative measure of quality for these and any other tracer formulations that we wish to compare; and that can eventually be related to visual perception.

Four candidate tracer formulations, including the existing baseline tracers, were identified and tested for emissivity and burn time in each of the desired spectral bandwidths, beginning with the red. For each recording, the x-axis is marked off in 500 msec intervals, and the y-axis varies between 0.2 and 2.0 volts per major division. Two tracer formulations are compared side by side and with respect to each other when fired statically and dynamically at 21,000 rpm. The graphs can be calibrated in luminous radiance in watts/steradian, using the calibration factors from Section 5. In addition, the observed color quality was noted with the measured intensity, in order to compare visual perception with the quantitative measurement.

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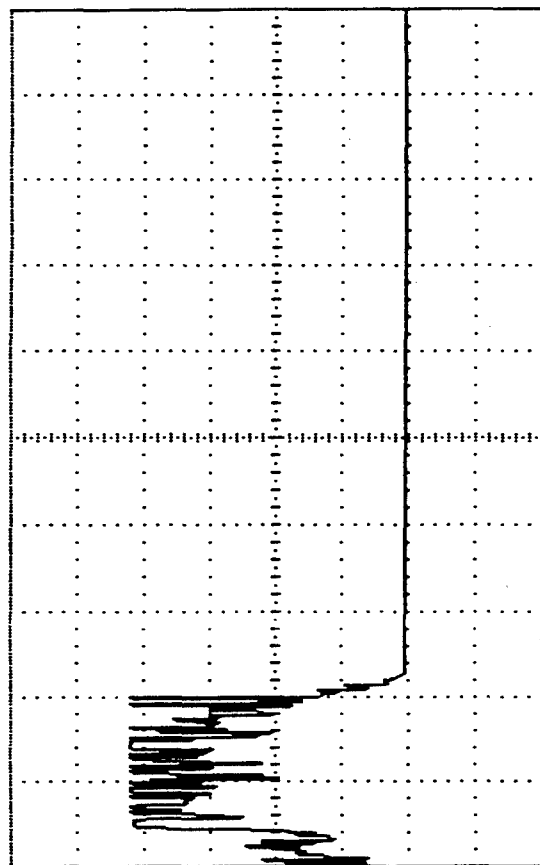
6.2 Alternate Red Tracer Formulations

The red tracer (Band 5) intensity vs. time plots are shown in Figures 13 (a)-(d). The curves in this figure were taken with the tracer spectrometer set to its lowest sensitivity, and recorded at 2 volts/vertical division, and 500 milliseconds /horizontal division. For the lowest sensitivity in Band 5, the calibration constant is 121.24, and the radiant intensity is, therefore, 445 milliwatts/SR/volt. Each major vertical division represents .890 watts/SR, in the specified red band. Figure 13-a. is the baseline existing red tracer for the 7.62mm projectile. Spinning, it burns for approximately three seconds with measurable intensity at this wavelength band. It is interesting to note in these charts that under dynamic conditions, the intensity always decreases and the burn time, in most cases increases. (The exceptions in the burn rate changes may be due to variability in subsequent tracer loads.) Reasons for this phenomenon may involve the use of the compressed air driven drill to spin the projectile. During spinning, the compressed air is vented rearward over the tracer slug simulating air flow which would occur during flight, although at considerably reduced velocity from the Mach 3 air flow that exists during actual bullet flight. The effect may be that heat flow through the wall of the bullet and cooling due to the rushing air was increased, resulting in a cooling of the combustion front in the tracer. After firing the tracer statically and dynamically, the slug body was perceptibly cooler to the touch after spinning in the air drill.

An additional observation relating to the difference in performance of the spinning and non-spinning combustion was that the rushing air elongated the tracer plume up to eight inches behind the bullet base. When fired statically, the tracer plume extended about two inches and then curved slightly upward due to the suction of the hood fan. The elongated plume during spinning may have had the added effect of drawing heat away from the combustion front quicker, resulting in a reduced burning rate and energy output. This may be similar to what would happen in actual flight.

Figures 13-b, c, and d are alternate red formulations developed to increase intensity of the spectral output, adjust burn time, or enhance red color quality over the baseline tracer formulation in Figure 13-a. Interestingly, the formulation in 13-b gives a

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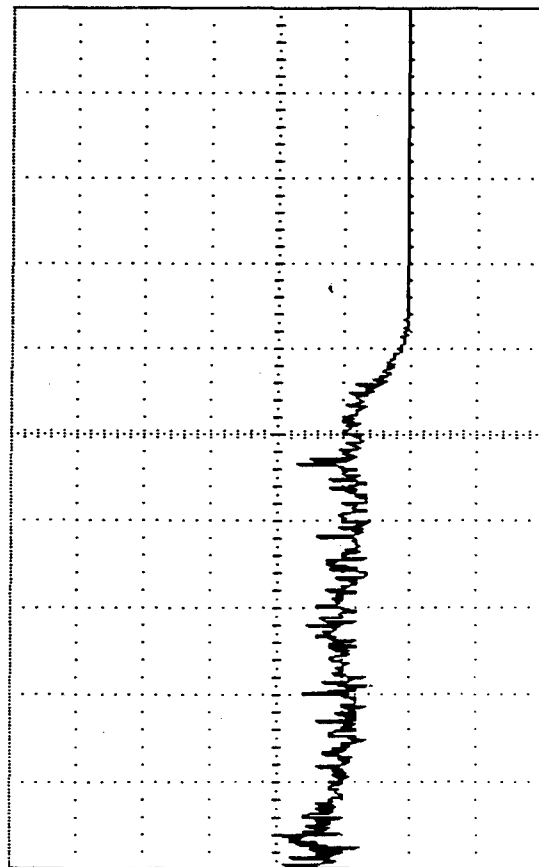
red.11

Strontium Nitrate / Mg / PVC
55 28 17

-2.0 V; 500 mS

red-e.2

Strontium Peroxide / Strontium Oxalate / Mg / PVC
40 15 30 15



13(a)

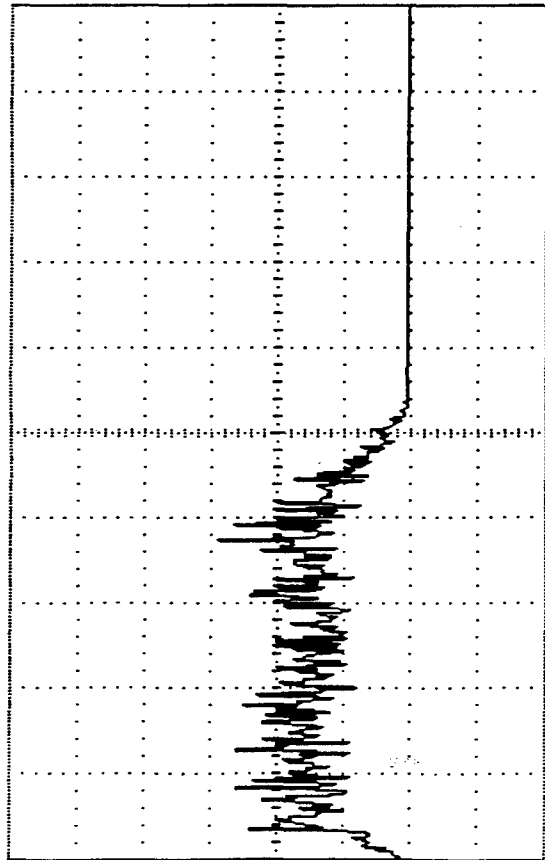
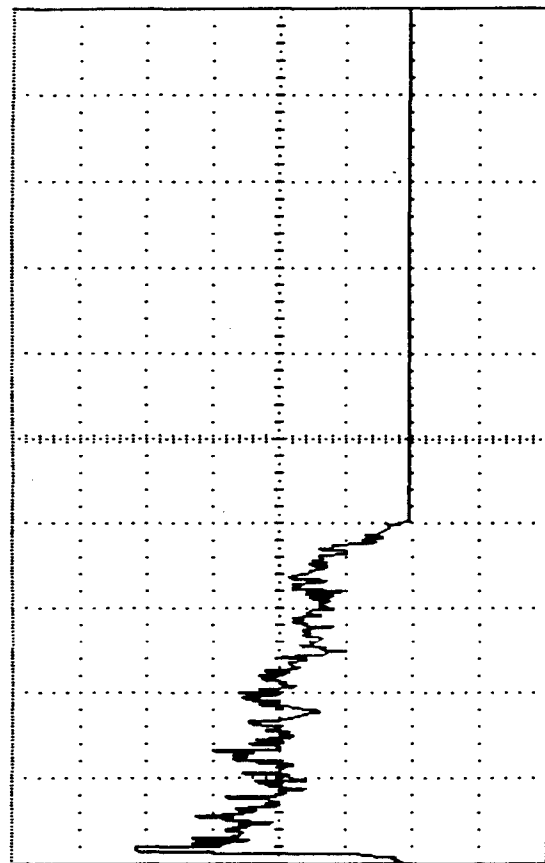
red.10s

-2.0 V; 500 mS

13(b)

red-e.4sp

Figure 13 - Band 5 (RED) Intensity vs. Time Plots

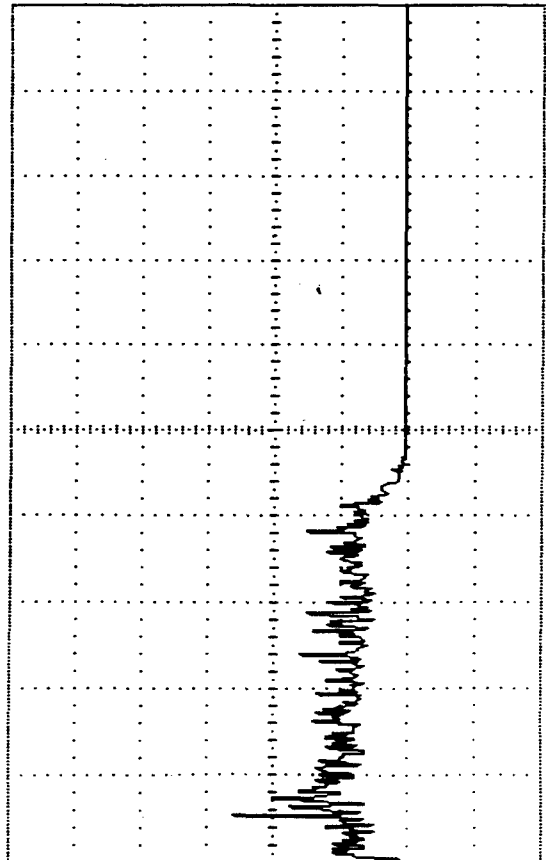
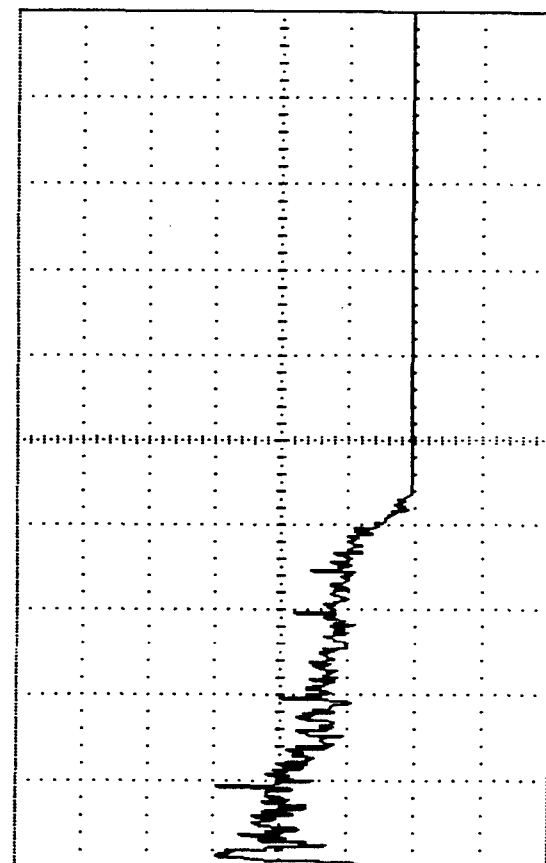


red-b.2

red-d.2

Strontium Nitrate / Strontium Oxalate / Mg / Hexachloroethane / PVC
31 12 35 12 10

Lithium Nitrate / Strontium Oxalate / Mg / PVC
31 21 32 16



red-d.4sp

red-b.3sp

13(c)

13(d)

Figure 13 - Band 5 (RED) Intensity vs. Time Plots

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clear indication of the result of increasing the metallic fuel to oxygen ratio in the mixture, while keeping ratios of other components largely the same. Referring to Table 5, which breaks out the salient chemical characteristics of the red tracer formulas, the baseline formula has a magnesium to oxygen ratio of about 1.1:1. Formula 13-b has a magnesium to oxygen ratio of about 1.9:1. Both have nearly the same percentage of organic fuel (PVC). The result of the greater magnesium to oxygen content of 13-b is that the mixture burned much faster and with greater intensity. The formulas in 13-c and 13-d were not affected as much by the disparity of magnesium to oxygen between each other, however, due to the increased content of organic fuel in 13-c. 13-c has a magnesium to oxygen ratio of 1.9:1, the same as 13-b; and 13-d has a ratio of 1.1:1, the same as 13-a. However, 13-c does not burn as fast as 13-b, since there is 7% more organic fuel which cools the burn and counteracts the burn rate enhancement provided by more magnesium. 13-d burns slightly faster than 13-a due to its slightly greater magnesium content and slightly reduced organic content, but not appreciably so. One interesting observation is that 13-b was perceived to have a much more intense red flame than was indicated by the measured intensity. It is felt that this formulation may be emitting in a portion of the red spectrum that is outside of the specified region, but within the sensitive region of the eye.

Table 5 -- Chemical Composition of Red Tracer Formulas

<u>13-a</u>	$Sr(NO_3)_2 / Mg / PVC$					<u>13-b</u>	$SrO_2 / SrC_2O_4 / Mg / PVC$				
	55 %	28	17				40 %	15	30	15	
Oxygen	25 %						16 %				
Strontium	23						37				
Magnesium	28						30				
Chlorine	9.5						8.4				
<u>13-c</u>							<u>13-d</u>				
$Sr(NO_3)_2 / SrC_2O_4 / Mg / HXE / PVC$						$LiNO_3 / SrC_2O_4 / Mg / PVC$					
	31 %	12	35	12	10			31 %	21	32	16
Oxygen	31 %							29 %			
Strontium	19							/Lithium 11			
Magnesium	35							32			
Chlorine	16							9			

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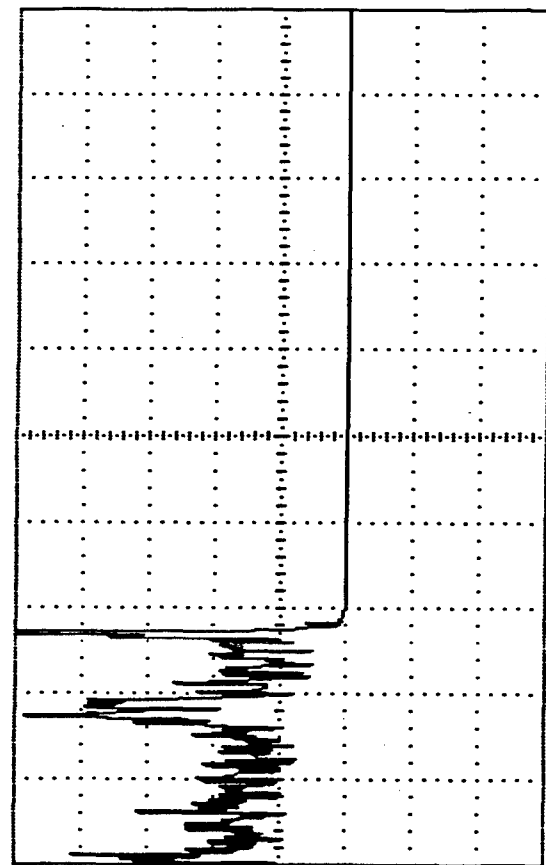
The amount of red light output could not be reliably correlated to the amount of strontium/lithium and chlorine present in the mixture, however. Formulas 13-c and 13-d have nearly equivalent strontium (and/or lithium) to chlorine ratios at about 1.2:1 each. However, formula 13-d has a slightly higher red intensity. This is perhaps due to the reduced burn time which results in the same amount of light energy being release at a higher average value. Formula 13-b, however, has more than four times the available strontium to chlorine at 4.4:1, and formula 13-a has a ratio of 2.4:1, strontium to chlorine. Excess strontium in 13-a does not seem to give it an advantage over 13-c and 13-d, so it is unlikely that it is contributing to the much higher intensity in 13-b. Most likely, the most efficient strontium to chlorine ratio is 1:1 since the red light emitting species is SrCl. In light of this, increasing both the strontium and chlorine content may perhaps be worthwhile.

6.3 Yellow Tracer Formulations

Figures 14 (a)-(c) show the results for candidate yellow (Band 3) tracer formulations. For the medium sensitivity in Band 3, the calibration constant is 16.84, and the radiant intensity is therefore 62.3 milliwatts/SR/volt. Therefore, each major vertical line represents 62.3 milliwatts/SR. This is significantly less than the equivalent red calibration, due to the narrower spectral width of the yellow portion of the spectrum. However, we can note from Figure 7, that the human eye is about 20 times more sensitive to yellow light energy than to red energy. This means that we need 20 times more red energy as yellow to perceive an equivalent brightness.

With yellow tracer formulations, since atomic sodium is responsible for yellow light emission, a correlation should appear with respect to the amount of sodium in the mixture and the emission intensity. This does appear when comparing 14-a and 14-b with 14-c and 14-d (Table 6). 14-c and 14-d clearly outperform the first two. The latter having sodium contents of 14 and 15%, respectively. In addition, 14-c and 14-d are burning appreciably longer so that no claim can be made that they are simply pushing out the same light energy at a higher average level. The two faster burning formulas 14-a and 14-b have less yellow light output, corresponding to less sodium content.

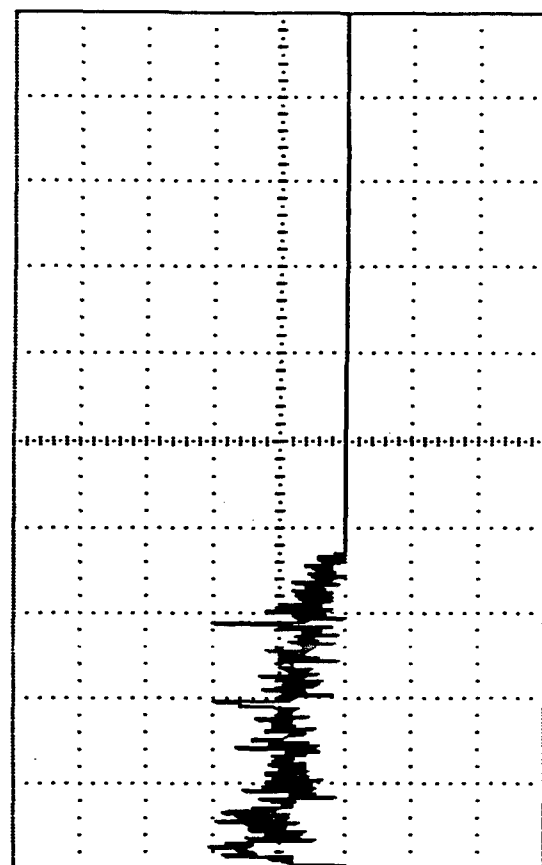
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yel-a.2

-1.0 V; 500 mS

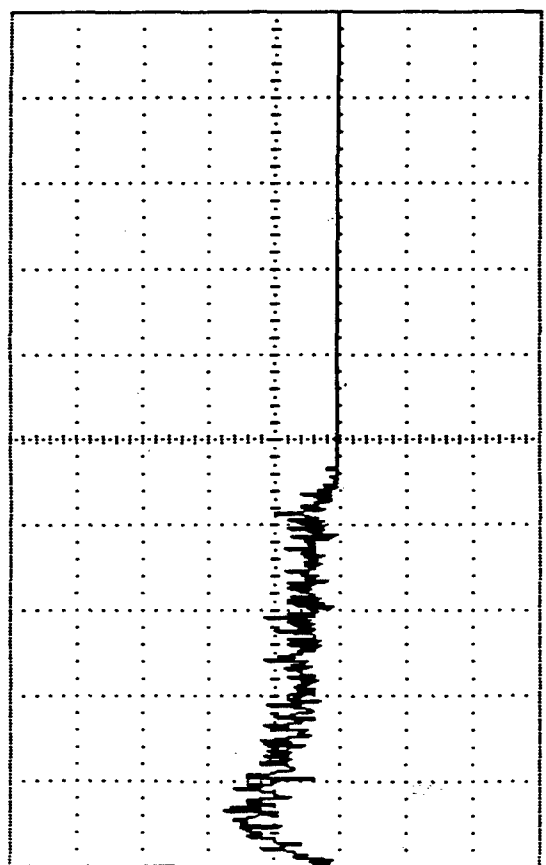
Sodium Perchlorate / Mg / PVC
46 % 37 17



yel-b.2

-1.0 V; 500 mS

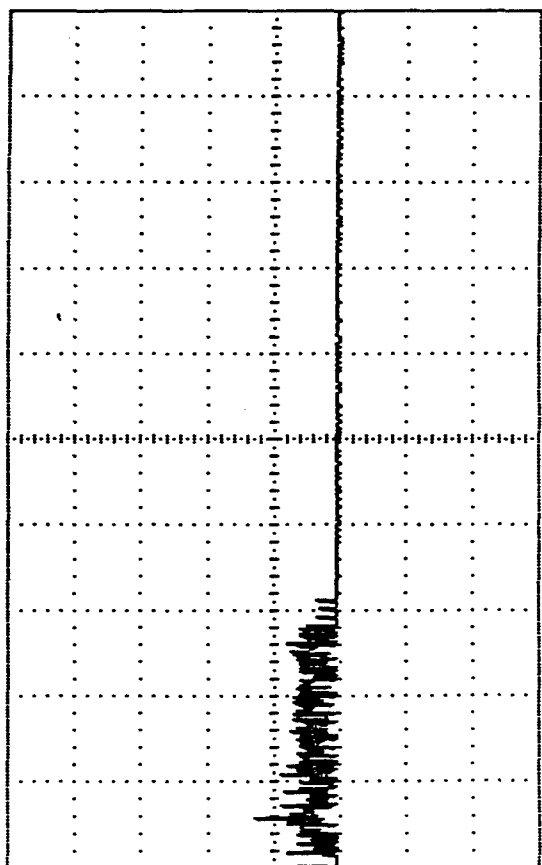
Barium Nitrate / Sodium Oxalate / Mg / PVC
37 % 12 40 11



yel-a.7sp

14(a)

Sodium Perchlorate / Mg / PVC
46 % 37 17

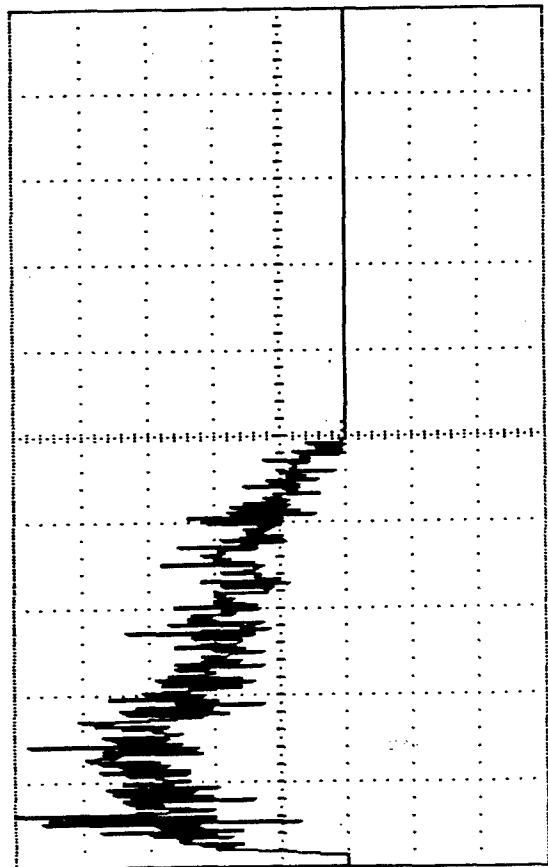


yel-b.3sp

14(b)

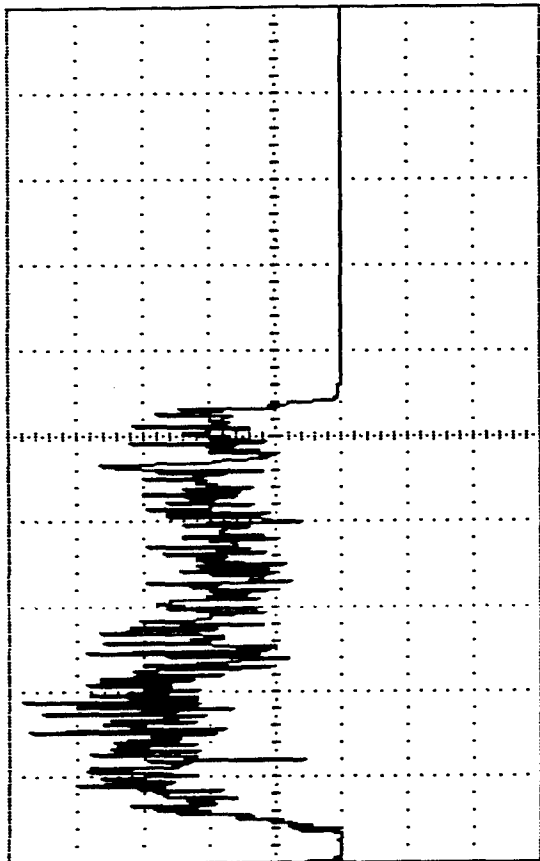
Barium Nitrate / Sodium Oxalate / Mg / PVC
37 % 12 40 11

Figure 14 - Band 3 (YELLOW) Intensity vs. Time Plots



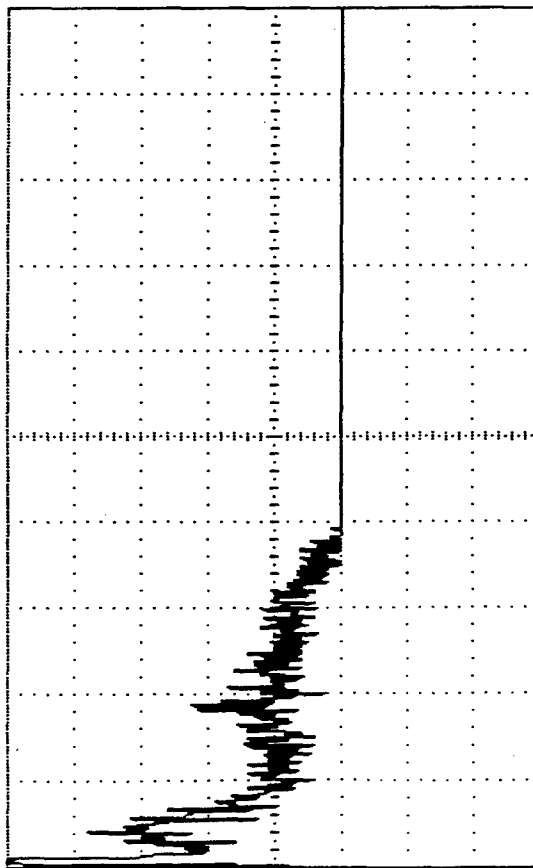
yel-c.1

Sodium Perchlorate / Sodium Oxalate / Mg / PVC
32 37 7



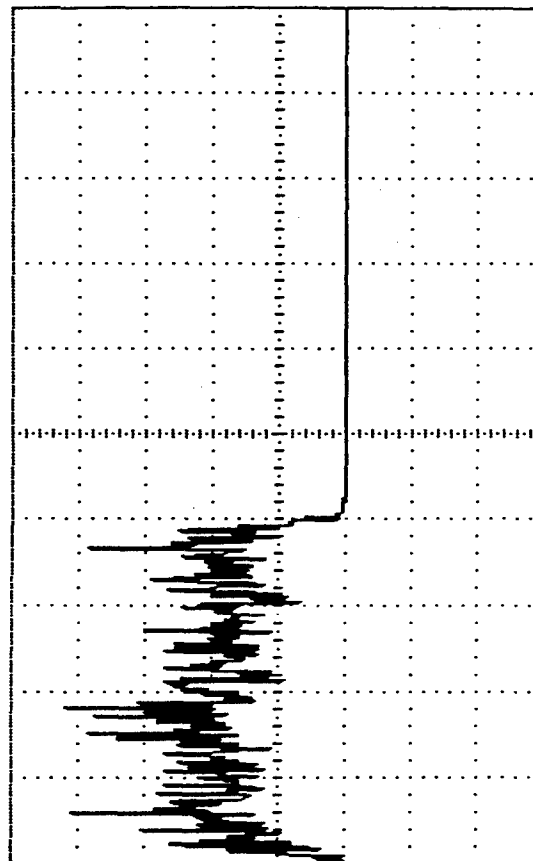
yel-d.1

Sodium Nitrate / Sodium Oxalate / Mg / PVC
30 40 10



14(c)

yel-c.2sp -1.0 0:500 mS



14(d)

yel-d.3sp

Figure 14 - Band 3 (YELLOW) Intensity vs. Time Plots

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Comparing 14-a with 14-b, however, shows competing reactions. 14-b has less sodium content than 14-a, 4% to 9%, respectively. Yet 14-b gives greater intensity than 14-a. This may be a burn rate effect. 14-b has a magnesium to oxygen ratio of 2:1, whereas 14-a has a ratio of 1.5:1. 14-a also has a larger percentage of organic fuel (PVC). 14-b should, therefore, burn faster, as it does in the chart. This is an argument that 14-b is emitting perhaps less light energy, but at a higher average value

Table 6 -- Chemical Composition of Yellow Tracer Formulas

14-a

NaClO_4 / Mg / PVC

46 % 37 17

Oxygen 24 %

Sodium 8.7

Magnesium 37

Chlorine 9.5

14-b

$\text{Ba}(\text{NO}_3)_2$ / $\text{Na}_2\text{C}_2\text{O}_4$ / Mg / PVC

37 % 12 40 11

19.5 %

4

40

6

14-c

NaClO_4 / $\text{Na}_2\text{C}_2\text{O}_4$ / Mg / PVC

32 % 24 37 7

Oxygen 28 %

Sodium 14

Magnesium 37

Chlorine 4

14-d

NaNO_3 / $\text{Na}_2\text{C}_2\text{O}_4$ / Mg / PVC

30 % 20 40 10

26 %

15

40

5.6

over its burn time. A suggestion for optimizing the performance of these tracer formulas, at least 14-b, c, and d may be to further reduce the organic fuel content, and boost burn rate so that each formulation emits at a higher average intensity over the desired burn time.

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6.4 Green Tracer Formulations

Figures 15 (a)-(d) show the intensity output for the candidate green tracer (Bands 1 + 2) formulations developed under this task. As has been previously discussed, the bandwidth for the green tracer was considerably larger than for the other colors, and the measurements had to be split into two distinct bands due to the fact that the filter slit was larger than any available silicon photodetector. Therefore, for each formula, the lower half of the band is given on the left, and the upper half on the right, with one formula on each page. As with the other colors, the upper graphs are for static firing of the tracer, and the lower graphs are the results when spinning. The bands are divided such that the total intensity output is simply the addition of each of the outputs in each band. Since the output of both green bands (Band 1 and Band 2) were recorded using the medium sensitivity position, the calibration constants, from Table 3, are 28.02 and 21.62 respectively, and the radiant intensity is 103.7 and 80.0 watts/SR/volt. Since the recordings were made a 2 volts/major division, the output calibration is 207 and 160 watts/SR/major division. The total in-band green energy is the sum of Band 1 and Band 2.

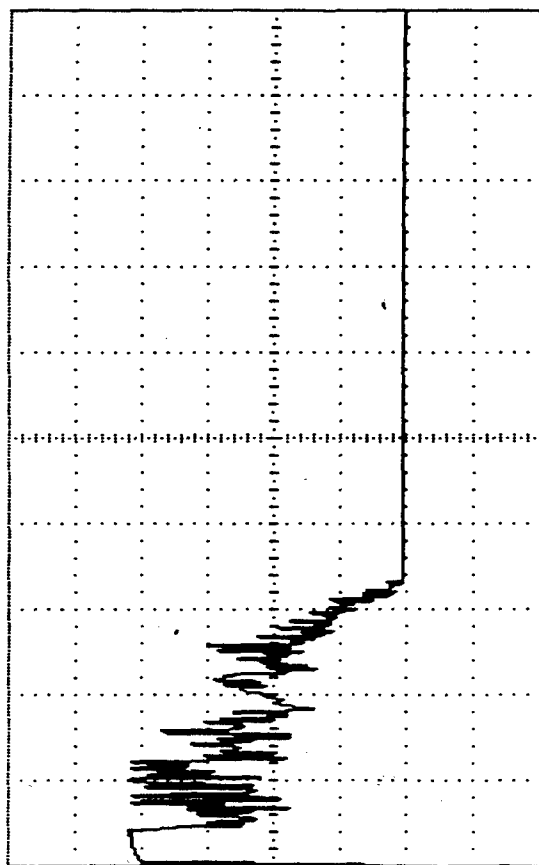
The trends with the green tracer formulas pattern those of red, since the light emitting species is BaCl. Formula 15-a burns fastest and with greater intensity, given that it has the greatest proportion of magnesium to available oxygen (2.2:1) (Table 7). Formulas 15-b and 15-d each have ratios of approximately 1.4:1. All three of these have similar barium and chlorine contents, between 26 and 28% for barium and 8 to 9.5% for chlorine. Therefore, the higher intensity for formula 15-a can be attributed to a shorter burn time.

Formula 15-c, however, is somewhat of an anomaly. It has a magnesium to oxygen ratio of 1.5:1, and the same percentage of organic fuel, PVC at 9.5%, which should imply that it would burn at the same rate as 15-b and 15-d, or very close. However, its burn time is exceptionally short (0.75 seconds). It is, nevertheless, very different from the other formulas in that it has the lowest overall magnesium and oxygen content, 18 and 12% respectively, and the highest barium content, 53%. One possible explanation for the fast reaction rate and poor color intensity output is that

GREEN

(.493-.530)

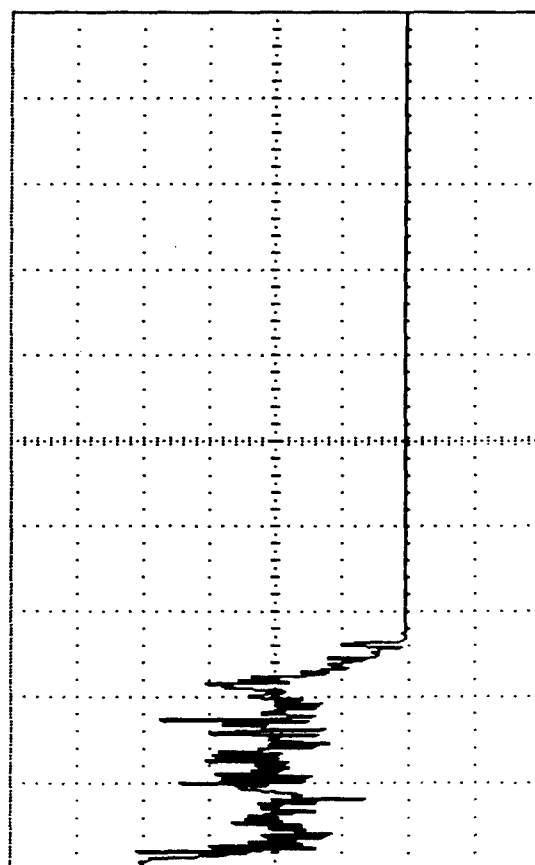
(.53-.572) Medium Sensitivity



grn-b1.9

=2.0 V; 500 mS

grn-b2.7



Band 1

grn-b1.10s =2.0 V; 500 mS

grn-b2.8sp

Band 2

Barium Nitrate / Mg / Dechlorane
50 40 10

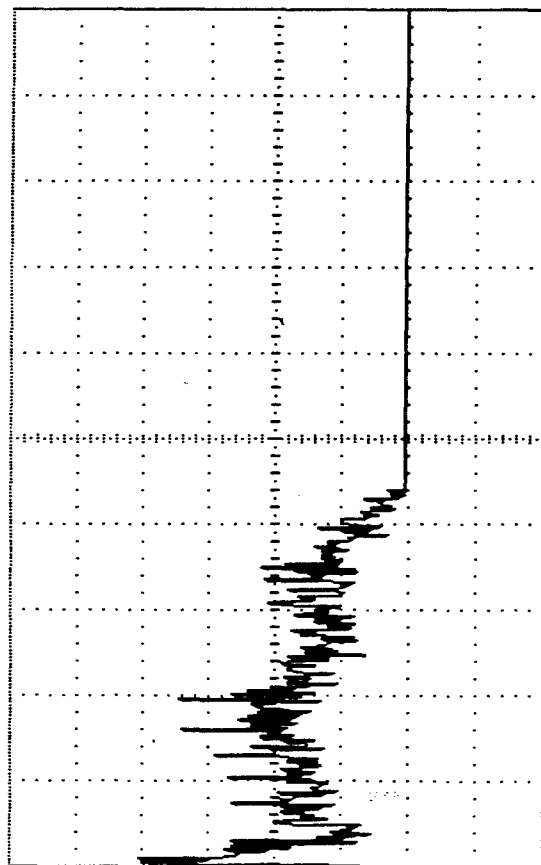
Figure 15(a) - (GREEN) Intensity vs. Time Plots

21000 rpm

GREEN

(.493-.530)

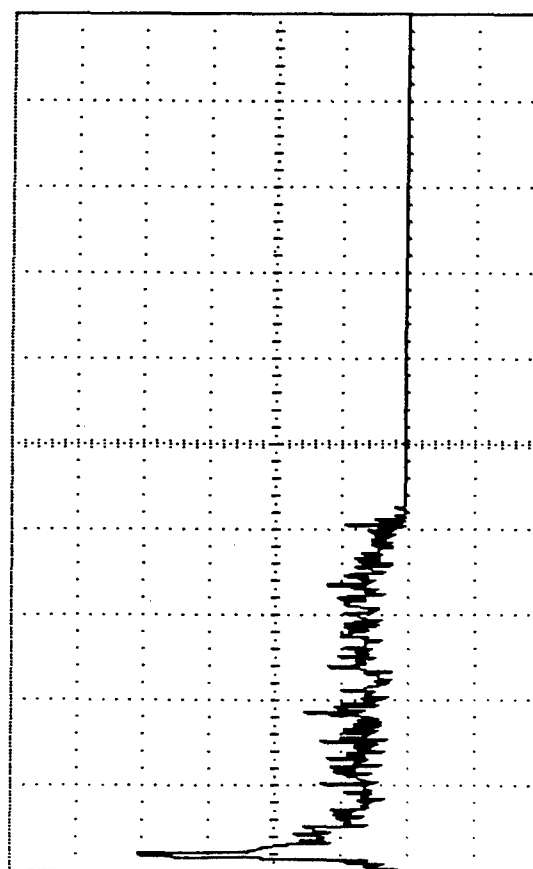
(.53-.572) Medium Sensitivity



grn-a1.2

=2.0 V; 500 mS

grn-a2.4



Band 1

grn-a1.3sp =2.0 V; 500 mS

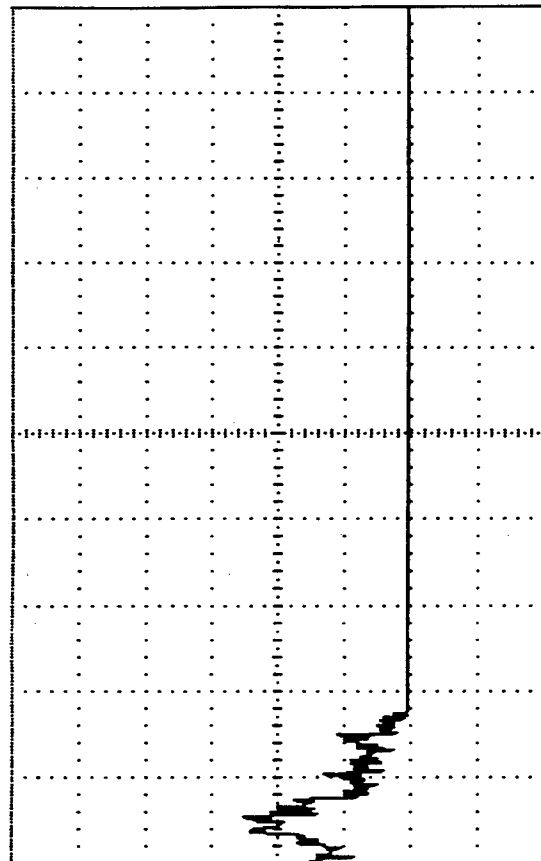
grn-a2.5sp

Band 2

Barium Nitrate / Mg / PVC
54 %
29
17

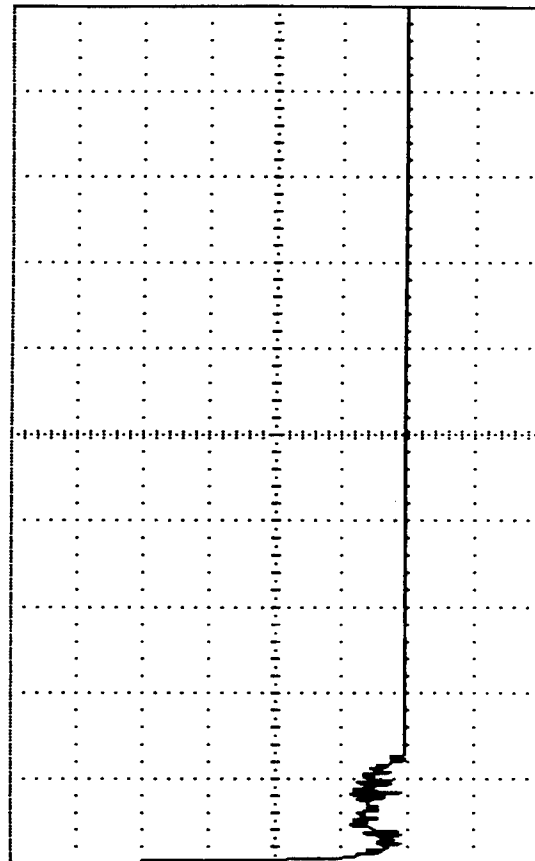
Figure 15(b) - (GREEN) Intensity vs. Time Plots

21000 rpm



gm-c2.13

gm-c1.11 =2.0 V;500 MS



gm-c2.14s

gm-c1.12s =2.0 V;500 MS

Band 2

Band 1

Barium Peroxide / Mg / PVC
65 18 17

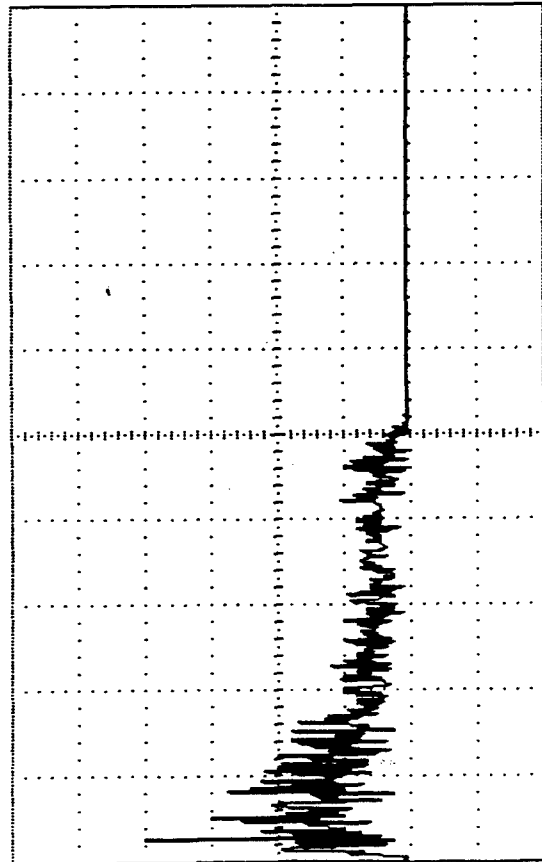
Figure 15(c) - (GREEN) Intensity vs. Time Plots

(.493-.530)

GREEN

(.53-.572)

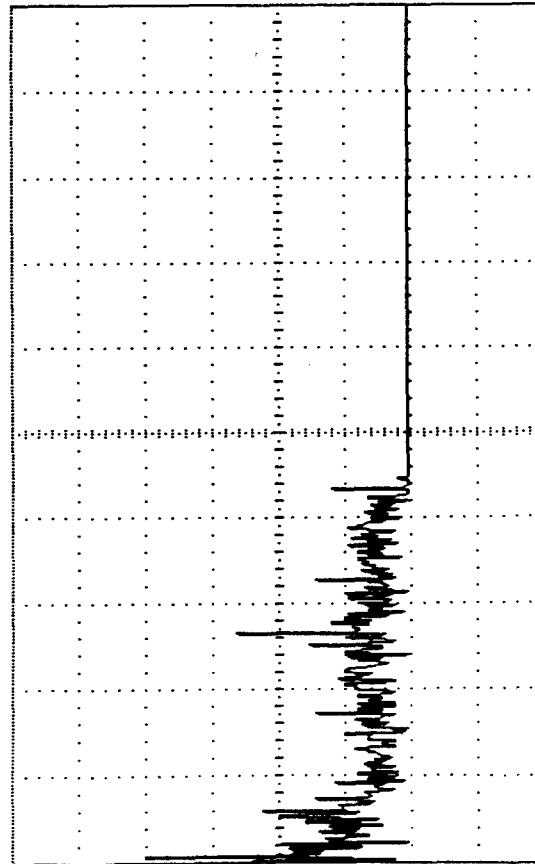
Medium Sensitivity



grn-d1.17

=2.0 V;500 mS

grn-d2.15



Band 1

grn-d1.18s =2.0 V;500 mS

Band 2

grn-d2.16s

Barium Chlorate / Mg / PVC
57 26 17

Figure 15(d) - (GREEN) Intensity vs. Time Plots

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Table 7 -- Chemical Composition of Green Tracer Formulas

15-a

Ba(NO₃)₂ / Mg / Dechl.
50 % 40 10

Oxygen 18.5 %
Barium 26.3
Magnesium 40
Chlorine 7.8

15-b

Ba(NO₃)₂ / Mg / PVC
54 % 29 17

20 %
28.4
29
9.5

15-c

BaO₂ / Mg / PVC
65 % 18 17

Oxygen 12 %
Barium 53
Magnesium 18
Chlorine 9.5

15-d

Ba(ClO₃)₂ / Mg / PVC
57 % 26 17

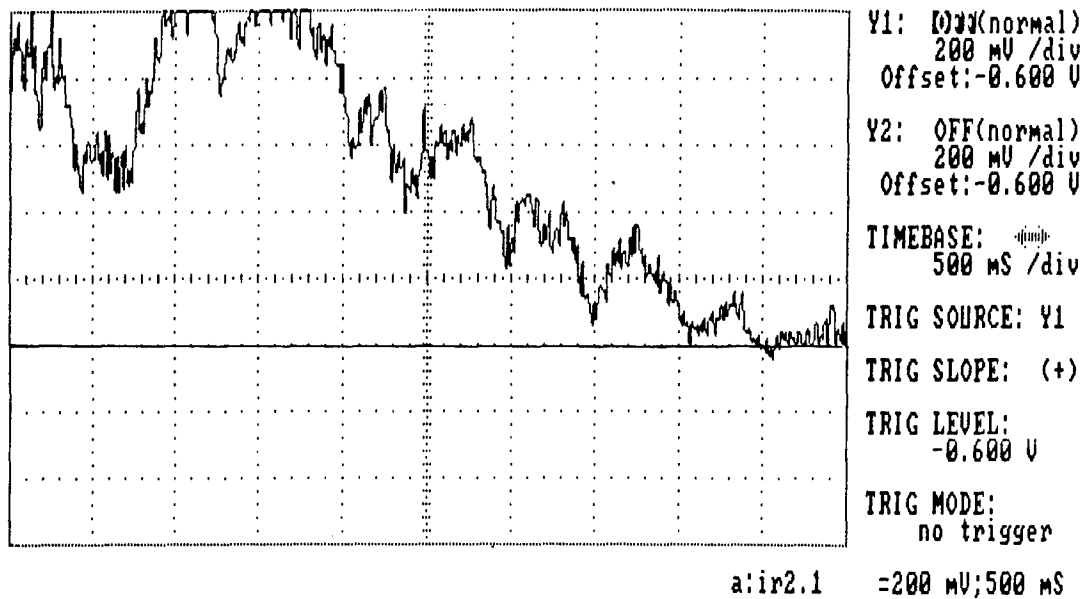
18 %
18
26
9.5

the magnesium and oxygen content was sufficient to initiate and sustain combustion, but that sufficient heat conduction preceded the burning surface, decomposing all of the barium peroxide with substantially nothing for the barium to do and not enough magnesium and oxygen to greatly excite what little BaCl was generated. A corollary to this explanation is that BaO₂ is found in tracer igniters, which implies a need for an oxidizer with a low decomposition temperature and a fast reaction rate.

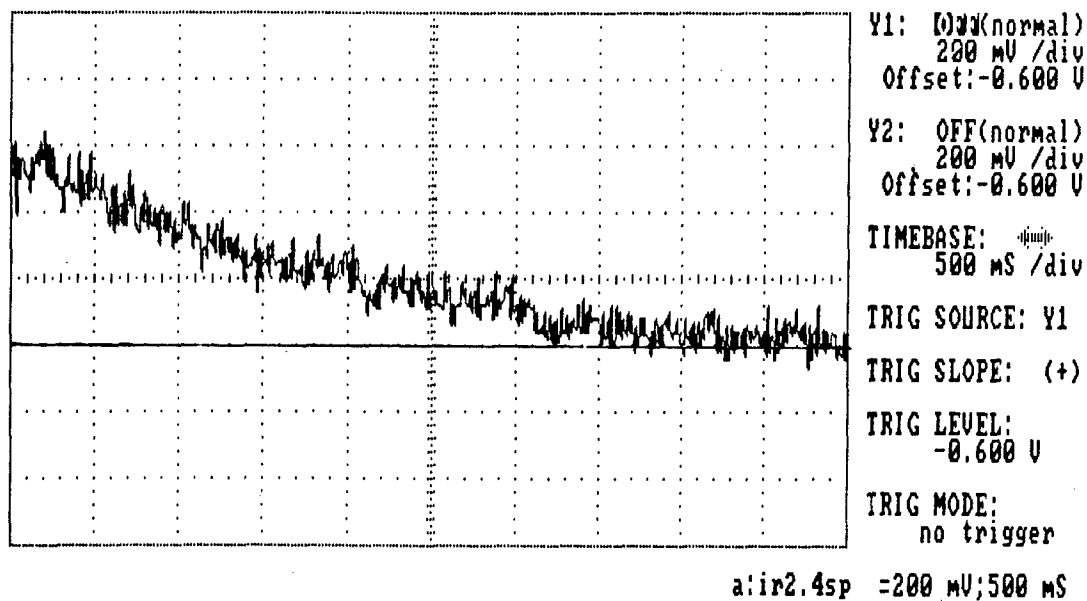
6.5 Alternate Infrared Tracer Formulations

Figures 16(a) and 16(b) show intensity results for the infrared tracer formulas developed in this task. In order to formulate an infrared tracer, it is necessary to keep the flame cool enough so that the blackbody radiation will predominate. If the temperature is adjusted properly, this relatively cool flame will give minimal visible light

Potassium Nitrate / Shellac
70 % 30

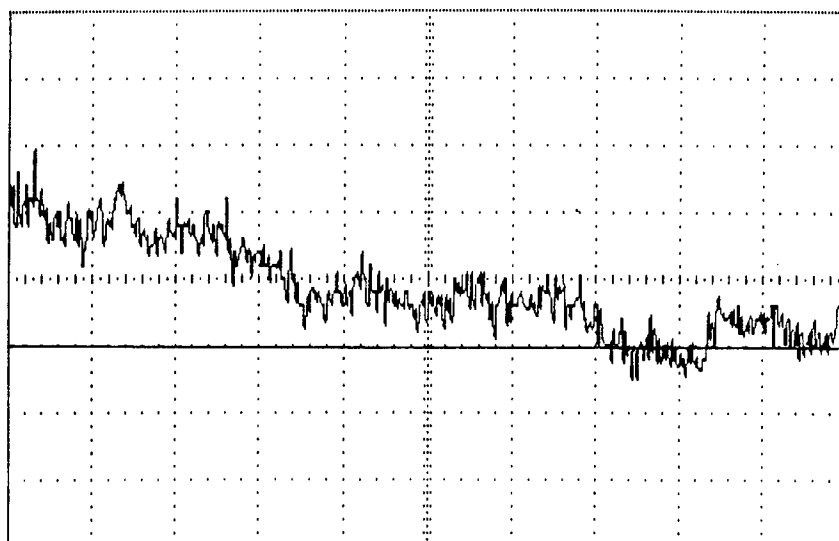


Static



Dynamic 21000 rpm

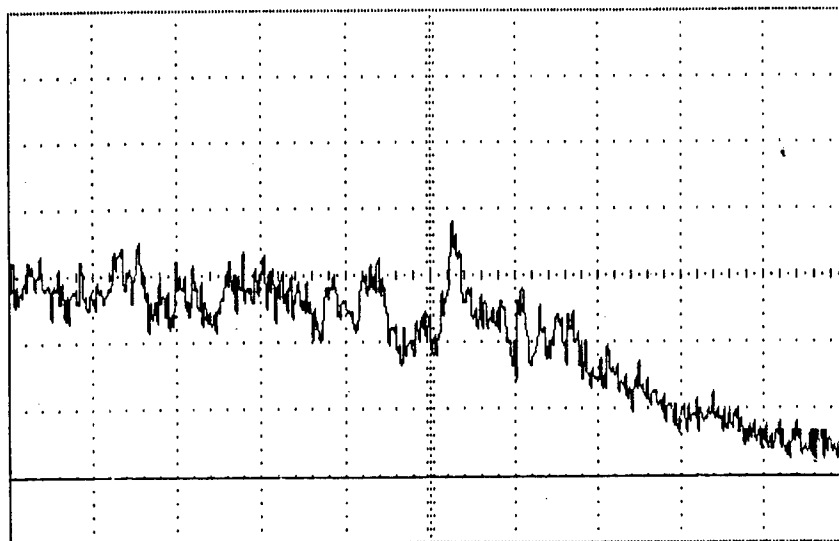
Figure 16(a) - Infrared Detector Calibration Data



Y1: [0]V(normal)
 200 mV /div
 Offset:-0.600 V
 Y2: OFF(normal)
 200 mV /div
 Offset:-0.600 V
 TIMEBASE: 500 ms /div
 TRIG SOURCE: Y1
 TRIG SLOPE: (+)
 TRIG LEVEL:
 -0.600 V
 TRIG MODE:
 no trigger

a:ir1.1 =200 mV;500 ms

Potassium Nitrate / Sodium Oxalate / Shellac
 70 % 10 20

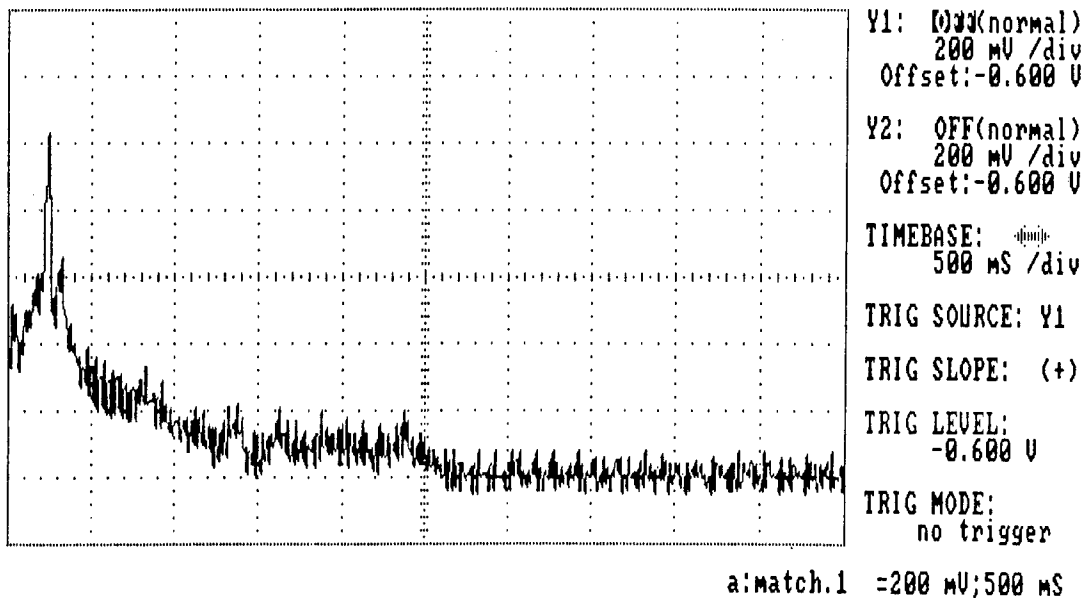


Y1: [0]V(normal)
 200 mV /div
 Offset:-0.600 V
 Y2: OFF(normal)
 200 mV /div
 Offset:-0.600 V
 TIMEBASE: 500 ms /div
 TRIG SOURCE: Y1
 TRIG SLOPE: (+)
 TRIG LEVEL:
 -0.600 V
 TRIG MODE:
 no trigger

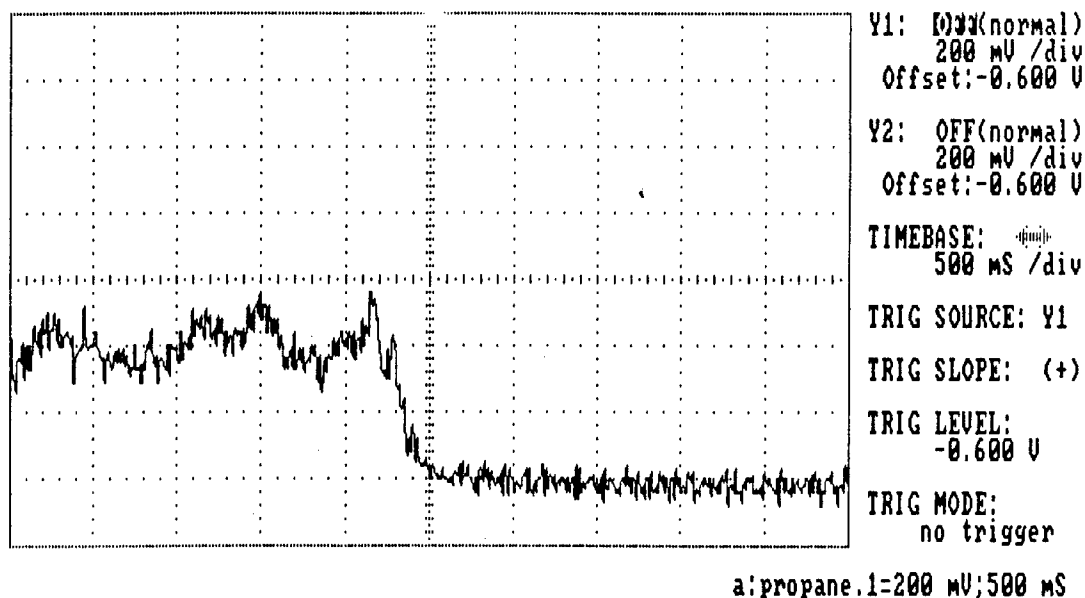
a:ir3.1 =200 mV;500 ms

Lithium Nitrate / Shellac
 70 % 30

Figure 16(b) - Infrared Detector Calibration Data



Match



Propane Torch

Figure 17 - Infrared Detector for Match and Propane Torch

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output, but will provide sufficient IR output in the desired bandwidth. Therefore, none of these formulas contain metallic fuel. Shellac was the organic fuel of choice owing to its low reaction temperature with oxygen, therefore, its ability to easily ignite. Several oxidizer/shellac combinations were tested to find the highest percentage of shellac which would ignite and burn smoothly. Only the formula in Figure 16(a) would sustain combustion when spinning. Each of two formulas in Figure 16(b) extinguished due to the rushing air of the drill. Even when ignited statically and then spun up, tracer combustion would stop. Using the IR calibration data from Table 4, and the 200 millivolts/major division on the recorder, the scale is 30 milliwatts/SR in the IR band. This number is not useful without knowing the sensitivity of the NV equipment.

The baseline dim tracer formula was also tested, and it ignited and burned smoothly both statically and dynamically. However, its infrared output, in this bandwidth, was so low that it did not register above background for the detector. In this respect, the formula in Figure 16(a) represents a significant increase in IR tracer performance. To put this in perspective, figure 17 shows the IR output for a standard match and the flame of the propane torch used to ignite the tracers during testing. Formula 16(a) performs substantially better than both when fired statically and better than a match when spinning. The first second of burn time when spinning, however, is at the same output level as the propane torch.

6.6 Observations of Color Quality vs. Measured Intensity

Table 8 summarizes the measured intensity of the candidate tracer formulations with respect to the subjective color quality observed by the test personnel. This information describes the complexity of developing quantitative scientific information about tracer performance and correlating this to observed tracer performance. An explanation of the inverse relationship between green color quality and measured intensity is that high intensity white light contains significant levels of green light. Since the detector was only measuring the green bandwidth, it could not indicate the level of undesirable light output, which was clearly beginning to obscure or wash out the desired green color in the highest intensity formula. As the flame temperature of the tracer cools, however, the white light blackbody radiation subsides, less BaCl disassociates in the flame due to high temperature, and a deeper green color emerges. However, overall green intensity is reduced as measured by the detector.

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Table 8 - Tabulation of Visual Perception with Quantitative Intensity Measurement

<u>Formula</u>	<u>Color/Quality</u>	<u>Measured Intensity</u>
<i>Barium Nitrate/Mg/Dechlorane</i>	<i>light green</i>	<i>highest</i>
<i>Barium Nitrate/Mg/PVC</i>	<i>green</i>	<i>lower</i>
<i>Barium Peroxide/Mg/PVC</i>	<i>green</i>	<i>lower</i>
<i>Barium Chlorate/Mg/PVC</i>	<i>deep green</i>	<i>lowest</i>
<i>Sodium Perchlorate/Mg/PVC</i>	<i>light yellow</i>	<i>lowest</i>
<i>Sodium Nitrate/Sodium Oxalate/Mg/PVC</i>	<i>yellow</i>	<i>lower</i>
<i>Sodium Perchlorate/Sod. Oxalate/Mg/PVC</i>	<i>yellow</i>	<i>lower</i>
<i>Sodium Nitrate/Sodium Oxalate/Mg/PVC</i>	<i>deep yellow</i>	<i>highest</i>
<i>Strontium Peroxide/Str. Oxalate/Mg/PVC</i>	<i>deep red</i>	<i>highest</i>
<i>Lithium Nitrate/Strontium Oxalate/Mg/PVC</i>	<i>red</i>	<i>lower</i>
<i>Strontium Nitrate/Mg/PVC</i>	<i>red</i>	<i>lowest</i>
<i>Strontium Nitrate/Str. Oxalate/Mg/HXE/PVC</i>	<i>red</i>	<i>lowest</i>

With yellow tracer formulas, however, the opposite color/intensity relationship is true. Since atomic sodium is responsible for the yellow color output, there is no molecule in the flame to disassociate reducing color output, and the greater the temperature, the greater the amount of yellow light emitted. At some point, however, blackbody radiation will obscure the yellow light, but this begins at temperatures above practical tracer formulations. A disadvantage, however, to using high temperatures to generate high intensity yellow traces is that the bullet may not be able to withstand the heat fluxes and could actually disintegrate in flight due to thermal softening. The practical limits of this should be determined.

The red tracer formulations developed in this task proved to be somewhat frustrating in terms of affecting red color quality. Red color quality should have performed in the same pattern as the green did -- color depth inversely proportional to intensity output. Although various levels of in-band energy were measured, no appreciable color difference was observed. A possible explanation is that the disassociation of SrCl is less sensitive to flame temperature than BaCl is. Therefore, deeper red flames are only possible at temperatures significantly cooler than those

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tested. This possibility was observed when developing the IR tracers, where slightly more reactive formulas had a very short, deep red flame. However, the intensity of the flame was unpractical for a visible tracer, and did not even register on the red detector. In addition, the desired red bandwidth is above the characteristic emissions of SrCl, so that only fringe readings are being made. These extreme emissions may be more susceptible to slight temperature variations than are possible to discern with the eye.

It is interesting to compare the energy output in watts/steradian for the three colors. The red gives a large output, and the yellow a much smaller output. However, Figure 7 shows that the threshold of the human eye is about 20 times more sensitive to the yellow light. Therefore the human perception is about the same. This is not in contradiction with our visual observations. For the case of the green, the human eye is about as sensitive as for the yellow, and the green output is higher than for the yellow. This implies that green may be a better color for tracers than the traditional red.

Several conclusions can be reached. First, there is at least one red tracer formulation that is superior to the current red tracer. The current tracer has an unnecessarily long burn time, and formulation (b) was more intense with a shorter burn time, although it will burn for the 1.6 second maximum time of flight. There are several formulations for green and yellow that will give bright traces for at least the bullet flight time. In the case of the infrared, we have a slightly more intense formulation but, since there is not visual perception, we need to compare it using the current night vision equipment.

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Section 7

Recommendations

The feasibility of deploying caliber 7.62mm (and other calibers) ammunition with tracer colors different than the current red has been demonstrated. This demonstration is supported by a quantitative methodology for comparing tracer performance and correlating this performance with visual observation. On the basis of both visual observations and quantitative measurements, we are recommending the following baseline formulations be considered:

<i>Red</i>	<i>13(b)</i>
<i>Yellow</i>	<i>14(d)</i>
<i>Green</i>	<i>15(a)</i>
<i>Infrared</i>	<i>16(a)</i>

In order to ensure that this work is utilized in a useful fashion, it may be advisable to consider several follow-on efforts in order to ensure that the performance of the various tracer formulations is optimized, and that ammunition manufactured with the alternate tracers performs as expected. The potential efforts that immediately suggest themselves are as follows:

1. The first consideration is that tracers have typically been formulated in an ad hoc way, and there is a dearth of quantitative data on existing production formulations. We, therefore, have only a very weak quantitative comparison between the existing red tracer with the new formulation that we feel will be substantially brighter. Now that the instrumentation exists, we feel that it would be useful to make a series of comparative measurements between the two formulations, in a controlled way, where the data is digitally recorded.

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2. Another issue is the relationship between scotopic (night) color perception (assuming tracers are used primarily at night) and tracer color. This is suggested by noting that the red tracers emit considerably greater in-band energy, yet are apparently no more perceptible than other colors. This is explained from the chart in Figure 7, where it is noted that the eye can be up to 100 times more sensitive to blues and greens than to red, and is also more sensitive to yellow - although to a lesser extent. When we compare the output data to the eye response in Figure 7, it seems probable that the green tracer formulation we have presented is superior to either of the red formulations. This suggests that tracer color can be optimized to maximize visual perception, with the least output energy. The results to date indicate that it may make sense to consider a blue-green tracer, as having several advantages over the current red.
3. Although we have, as the task order specified, derived and supplied the necessary formulations that have the request properties, the next step remains to be done. We are now ready to fabricate several hundred of each composition in actual 7.62mm bullets, and then conduct field tests. In order to ensure that we can correlate the data, it is essential the fabrication be well controlled. This should entail numbering each bullet as it is loaded, and testing every tenth bullet. These tests should consist of visual observations and digitally recording intensity data for later examination, if necessary.
4. We have classified several tracers in terms of intensity and burn time, and we have some understanding of the phenomena differences and tradeoffs. When a formulation is accepted, it is important to precisely optimize the mixture and process in order to maximize the intensity over the desired burn time.

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